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**RADIATED EMISSIONS FROM HIGH FREQUENCY
POWERLINE TELECOMMUNICATIONS (PLT) SYSTEMS**

Iain Summers

BSc(Hons)

A thesis submitted to the Open University Faculty of Mathematics, Computing and
Technology for the degree of Doctor of Philosophy

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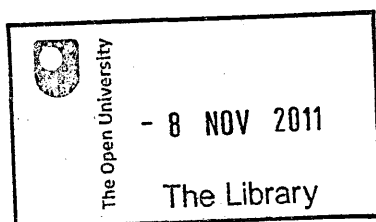
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ABSTRACT

The use of broadband Powerline Telecommunications (PLT) to deliver high speed services has been anticipated since the late 1990s. Due to its radiated emissions in the High Frequency (HF) band, the regulatory authorities have had difficulty in defining a repeatable measurement technique and an acceptable radiated limit for Electromagnetic Compatibility (EMC) compliance. Other researchers have undertaken work to predict, model or measure the effects on victim receivers but the uncertainty of the measurements is rarely discussed.

This thesis identifies the areas of uncertainty in PLT radiated emission measurements and recommends a method to account for the measurement errors. A measurement campaign was undertaken in urban, rural and semi-rural test sites in the UK to demonstrate the effects of antenna type, orientation and measurement distance. Furthermore for each measurement location, attenuation with distance properties are described which can be used in the prediction of PLT radiated emissions at a distance. Additionally the K-factor which had previously been thought to be a useful parameter is calculated at each location and is shown to be of little value in the determination of a "safe radiated emission limit" for PLT.

A novel test method of mutual interference testing is described which provides a more realistic demonstration of the effects of PLT radiated emissions on HF receivers. In conjunction with a risk mitigation strategy a compromise radiated emission limit is recommended that may facilitate the regulation of PLT.



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DECLARATION

The theory presented in chapter 3 is derived from a number of published sources on electromagnetics and EMC measurement and is included to put the work undertaken by others in Chapter 2 in context – specifically to demonstrate the inherent inaccuracy in EMC measurements. It is therefore not presented as original work as part of this research.

The experimental measurements discussed in Chapter 4 in Linz and in Canberra were undertaken by colleagues within the Power Systems Communication Research Group (PSCRG) at the Open University, but the analysis discussed was undertaken as original work by me as part of this thesis. All other measurements were designed and undertaken by myself with occasional support from colleagues within the PSCRG to operate equipment during information capture. I developed the software in chapter 4 to control the Anritsu 420B Network Analyser (10Hz – 30MHz) for the purpose of this thesis using the open source code modules provided by National Instruments as part of their product support for their GPIB interface card. All other experimental work reported in this thesis is original, except where acknowledged in the text or by reference.

The contents of this thesis have not been submitted to the Open University or any other establishment as part of a degree application and none of the work has been published previously. Generic aspects of the measurement techniques and some high level conclusions have been discussed in papers provided to the UK Government, the EU Commission and overseas government organisations.

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This work would not have been completed without the help and support of many others but I would like to specifically thank the following:

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CONTENTS

Abstracti

Declarationii

Acknowledgements..... iii

Contentsiv

Figures xii

Tables.....xv

Equations xvi

Constantsxviii

CHAPTER 1 - Background..... 1

 1.1 History of powerline telecommunication..... 1

 1.2 Powerline telecommunication 1

 1.2.1 Low frequency PLT 2

 1.2.2 High frequency PLT 2

 1.2.3 Access PLT 2

 1.2.4 In House PLT..... 3

 1.3 Potential PLT applications 3

 1.3.1 Broadband internet access 3

 1.3.2 Intra-building networking..... 4

 1.3.3 Video streaming..... 4

 1.4 Interoperability 4

 1.4.1 Radiated emissions 5

 1.4.2 Cumulative emission..... 5

1.4.3	Conducted emission/susceptibility	6
1.5	Regulation	6
1.5.1	Background	6
1.5.2	National (UK).....	6
1.5.3	EU	7
1.5.4	International.....	7
1.6	Electromagnetic Compatibility (EMC) standards and enforcement.....	7
1.6.1	EMC	7
1.6.2	National Standards	8
1.6.3	EU Standards	8
1.6.4	International Standards.....	9
1.7	Evidence to satisfy requirements	9
1.7.1	Theoretical prediction	10
1.7.2	Modelling	10
1.7.3	Measurement.....	10
1.8	Thesis Outline.....	11
1.8.1	Chapter 1 - Background.....	11
1.8.2	Chapter 2 – Existing research in HF powerline communication	11
1.8.3	Chapter 3 – Theory of EMC and PLT.....	11
1.8.4	Chapter 4 - Measurements	11
1.8.5	Chapter 5 – Summary of results	12
1.8.6	Chapter 6 – Other factors, conclusion and further work	12
1.9	Conclusion.....	12

CHAPTER 2 - Existing research in HF Powerline Communication 13

2.1 Theoretical prediction 13

2.1.1 Electronic Communications Committee of CEPT Report (May 2003) 13

2.1.2 Reports by researchers 14

2.1.3 Using ITU-R Noise Limits..... 16

2.1.4 Conversion of CISPR 22 (EN 55022) conduction limits to radiated limits.....17

2.1.5 Attenuation with distance 18

2.1.6 Cumulative effects 19

2.1.7 Summary of theoretical prediction..... 19

2.2 Modelling 20

2.2.1 Smith’s Report for the RA 20

2.2.2 NTIA Report 04-413..... 20

2.2.3 American Radio Relay League (ARRL) models 21

2.2.4 Summary of modelling 21

2.3 Measurement..... 22

2.3.1 Measurements in context..... 22

2.3.2 OfCom (RA)..... 22

2.3.3 DS2 system – Creiff, Scotland, UK 23

2.3.4 Main.net system – Creiff, Scotland, UK..... 24

2.3.5 ASCOM system – Winchester, England, UK..... 25

2.3.6 Amperion system – Creiff, Scotland, UK..... 26

2.3.7 British Broadcasting Corporation (BBC) reports..... 28

2.3.8	Global reports	28
2.3.9	Summary of Measurements	29
2.4	Summary	31
CHAPTER 3 - Theory of EMC and PLT		32
3.1	PLT	32
3.1.1	The power network	32
3.1.2	Access/In-house	35
3.2	Electromagnetic radiation	37
3.2.1	Lorentz force Law	38
3.2.2	Maxwell's Equations	40
3.2.3	Differential Form of Maxwell's Equations	44
3.2.4	Electromagnetic wave equation	47
3.2.5	Energy in an electromagnetic wave	48
3.2.6	An alternative view	50
3.2.7	Infinitesimal dipoles	52
3.2.8	Limitations	54
3.2.9	Near-field/far-field	55
3.2.10	Far-field/near-field boundary	59
3.2.11	Attenuation with distance	63
3.2.12	Conversion limitations of H to E using free space impedance	65
3.2.13	Common mode/differential mode	68
3.3	EMC	70
3.3.1	EU Directive 2004/108/EC	71

3.3.2	Conducted or Radiated Emissions?	73
3.3.3	Radiated emissions	77
3.3.4	Detectors	77
3.3.5	Antenna Type	79
3.3.6	Distance	80
3.3.7	Location.....	80
3.3.8	Antenna Factor	81
3.3.9	Artificial Mains Network	81
3.3.10	Measurement errors	82
3.4	Comparison of standards and methods	83
3.4.1	EMC Standards	84
3.4.2	Regulatory Standards	86
3.5	Summary	88
CHAPTER 4 - Measurements		90
4.1	Background	90
4.2	Measurements.....	90
4.3	Accuracy and uncertainty.....	91
4.3.1	Monte-Carlo analysis.....	93
4.3.2	Application of Monte-Carlo analysis to PLT measurement.....	95
4.3.3	Antennas	97
4.4	Results of PSCRG radiated emission tests	98
4.4.1	Rationale	98
4.4.2	Technique.....	99

4.4.3	Results	100
4.4.4	Results – 1 Maidenhead, UK – ASCOM & Main.net.....	100
4.4.5	Results – 2 Linz, Austria – Main.net.....	102
4.4.6	Results – 3 Canberra, Australia – DS2	104
4.4.7	Results – risk adjusted (Monte-Carlo).....	106
4.5	Measurement 2 – EMC analyser.....	106
4.5.1	Rationale	106
4.5.2	Technique.....	106
4.5.3	Date and Location	107
4.5.4	Results 4 – 39dBm with antenna perpendicular	112
4.5.5	Results 5 – 39dBm with antenna parallel	122
4.5.6	Results 6 – 39dBm vector sum of results 4 and results 5.....	123
4.5.7	Results 7 – -7dBm with antenna perpendicular.....	124
4.6	Measurement 3 – Difference between E and H.....	125
4.6.1	Rationale	125
4.6.2	Technique.....	126
4.6.3	Results 8 – 39dBm with monopole antenna	126
4.6.4	Results 9 – attenuation from real PLT modem	129
4.7	Measurement 4 – Network Analyser	134
4.7.1	Rationale	134
4.7.2	Technique.....	135
4.7.3	Results 10 – Urban premises – Bradley Stoke.....	138
4.7.4	Results 11 – Semi-Rural premises – Bridgwater.....	139

4.7.5	Results 12 – Rural premises – Milton Keynes.....	140
4.8	Measurement 5 - Mutual interference	142
4.8.1	Rationale	142
4.8.2	Technique.....	143
4.8.3	Results	146
4.9	Measurement 6 – K factor.....	148
4.9.1	Rationale	148
4.9.2	Technique.....	149
4.10	Summary	153
CHAPTER 5 - Summary of Results.....		154
5.1	Introduction.....	154
5.2	Summary of results.....	154
5.2.1	Radiated emission measurements.....	154
5.2.2	Attenuation with distance measurements.....	155
5.2.3	K-Factor measurements	158
5.2.4	Actual PLT effects	159
CHAPTER 6 – Other factors, conclusion and further work		161
6.1	Other factors.....	161
6.1.1	Political.....	161
6.1.2	Economic.....	163
6.1.3	Social	164
6.1.4	Subtle changes in regulation.....	165
6.1.5	Mitigation	167

6.1.6	Future factors	171
6.1.7	Conclusion.....	174
6.2	Overall conclusion	175
6.3	Further work	176
	Appendix A.....	179
	Appendix B	186
	Appendix C.....	193
	Appendix D.....	199
	Appendix E	205
	Appendix F	216
	Appendix G.....	231
	Appendix H.....	247
	Appendix I.....	263
	Glossary	283
	Bibliography.....	286

FIGURES

Figure 1-1 – EMC interference paths 8

Figure 3-1 – UK electrical distribution network 34

Figure 3-2 – ETSI TS 101 867 coexistence proposal 36

Figure 3-3 – Gauss’s Law 41

Figure 3-4 – Faradays Law 42

Figure 3-5 – Amperes Law (diagram)..... 43

Figure 3-6 – Re-radiation from the ionosphere (sky wave)..... 52

Figure 3-7 – Radiation from infinitesimal dipole..... 53

Figure 3-8 – Transverse electromagnetic wave..... 55

Figure 3-9 – Sinusoidal infinitesimal dipole showing E and H components 56

Figure 3-10 – Sinusoidal infinitesimal loop showing E and H components 58

Figure 3-11 – Electric and magnetic field strengths of infinitesimal sources 59

Figure 3-12 – Definitions of near-field/far-field boundary 61

Figure 3-13 – Two and three region models..... 62

Figure 3-14 – Differential and common mode currents..... 69

Figure 3-15 – Comparison of EMC limits..... 88

Figure 4-1 – Probability distribution functions..... 94

Figure 4-2 – University of Hertfordshire tuned antennas 97

Figure 4-3 – PLT emissions at Maidenhead, UK (ASCOM).....101

Figure 4-4 – PLT emissions at Maidenhead, UK (Main.net)102

Figure 4-5 – PLT emissions Linz, Austria (Main.net)103

Figure 4-6 – PLT emissions Linz, Austria (Main.net) with trend line103

Figure 4-7 – PLT emissions Canberra, Australia (DS2).....104

Figure 4-8 – Comparison of global rural noise105

Figure 4-9 – Bradley Stoke nr Bristol, UK - site location.....107

Figure 4-10 – Bradley Stoke premises electrical diagram108

Figure 4-11 – PSCRG LV coupler	109
Figure 4-12 – LV coupler – circuit diagram.....	110
Figure 4-13 – Attenuation with distance – test setup.....	111
Figure 4-14 – Attenuation with distance @ 1.6MHz	116
Figure 4-15 – Attenuation with distance @ 5MHz	117
Figure 4-16 – Attenuation with distance @ 10MHz	117
Figure 4-17 – Attenuation with distance @ 15MHz	118
Figure 4-18 – Attenuation with distance @ 20MHz	118
Figure 4-19 – Attenuation with distance @ 25MHz	119
Figure 4-20 – Attenuation with distance @ 30MHz	119
Figure 4-21 – Location of antenna during attenuation with distance test	121
Figure 4-22 – Antenna parallel @ 5MHz	122
Figure 4-23 – Antenna parallel @ 25MHz	123
Figure 4-24 – Comparison of PLT to ambient noise	130
Figure 4-25 – Attenuation with distance of Main.net PLT @ 3.5Mhz	131
Figure 4-26 – Attenuation with distance of Main.net PLT @ 7Mhz.....	132
Figure 4-27 – Attenuation with distance of Main.net PLT @ 10Mhz	132
Figure 4-28 – Attenuation with distance of Main.net PLT @ 13Mhz	133
Figure 4-29 – Attenuation with distance of Main.net PLT @ 17Mhz	133
Figure 4-30 - Attenuation with distance using network analyser – setup	136
Figure 4-31 – Comparison of sweep times to determine optimum.....	137
Figure 4-32 – Bridgwater College, Bridgwater, UK – site location	139
Figure 4-33 – Open University, Milton Keynes, UK – site location.....	141
Figure 4-34 – Mutual interference test – setup.....	144
Figure 4-35 – PLT vs ambient as baseline for mutual interference test	146
Figure 4-36 – K factor, 4 bedroom house, Bradley Stoke, UK @ 1m.....	149
Figure 4-37 – K factor, 4 bedroom house, Bradley Stoke, UK @ 3m.....	150
Figure 4-38 – K factor, 4 bedroom house, Bradley Stoke, UK @ 5m.....	150

Figure 4-39 – K factor, 4 bedroom house, Bradley Stoke, UK @ 7m.....151

Figure 4-40 – K factor, Bradley Stoke, UK @ 20V showing all distances151

Figure 4-41 - K factor, Bradley Stoke, UK @ 100mV showing all distances152

Figure 6-1 – ITU-R radio bands168

Figure 6-2 – Predicted PLT modem future roadmap171

TABLES

Table 2-1 – Separation required to ensure S/N ratio is not degraded by less than 0.5dB.	14
Table 4-1 – List of uncertainties in chapter 4 measurements	96
Table 4-2 – Assumptions for chapter 4 measurements	96
Table 4-3 – Coupling loss of LV coupler.....	110
Table 4-4 – Ambient noise @ 5m with antenna perpendicular	112
Table 4-5 – Attenuation with distance @ 1.6MHz.....	113
Table 4-6 – Attenuation with distance @ 5MHz	113
Table 4-7 – Attenuation with distance @ 10MHz.....	114
Table 4-8 – Attenuation with distance @ 15MHz.....	114
Table 4-9 – Attenuation with distance @ 20MHz.....	115
Table 4-10 – Attenuation with distance @ 25MHz.....	115
Table 4-11 – Attenuation with distance @ 30MHz.....	116
Table 4-12 – Comparison of directly measured E to derived E @ 1.6MHz.....	127
Table 4-13 – Comparison of directly measured E to derived E @ 5MHz	127
Table 4-14 – Comparison of directly measured E to derived E @ 10MHz	127
Table 4-15 – Comparison of directly measured E to derived E @ 15MHz	128
Table 4-16 – Comparison of directly measured E to derived E @ 20MHz	128
Table 4-17 – Comparison of directly measured E to derived E @ 25MHz	128
Table 4-18 – Comparison of directly measured E to derived E @ 30MHz	129
Table 4-19 – List of test frequencies	145
Table 4-20 – Definitions for sound quality	145
Table 4-21 – Assessment of interference to wanted signal	147

EQUATIONS

Equation 2-1 – Proposed magnetic field strength (Stott) based upon ITU-R 372.... 16

Equation 2-2 – Proposed electric field strength (Stott) based upon ITU-R 372..... 16

Equation 2-3 – K-Factor as a ratio 17

Equation 2-4 – K-Factor as a log 17

Equation 2-5 – K-Factor as log when units are expressed in logs 17

Equation 3-1 – The Lorentz force law 40

Equation 3-2 – Gauss’s Law 40

Equation 3-3 – Gauss’s Law applied to magnetic fields 40

Equation 3-4 – Faradays Law 40

Equation 3-5 – Amperes Law adjusted for displacement current..... 40

Equation 3-6 – Amperes Law in original form..... 43

Equation 3-7 – Gauss’s divergence theorem 45

Equation 3-8 – Stoke’s theorem..... 45

Equation 3-9 – Maxwell’s Equations simplified for free space 47

Equation 3-10 – Maxwell’s Third Equation with curl applied to both sides 47

Equation 3-11 – Equation 3-10 in terms of electric field 47

Equation 3-12 – Wave equation for the electric field 48

Equation 3-13 – Velocity of an electromagnetic wave in free space 48

Equation 3-14 – Derivation of the Poynting Vector..... 49

Equation 3-15 – Coulombs Law 55

Equation 3-16 – Near-field/far-field boundary for antennas 62

Equation 3-17 – Trzaska variation of near-field/far-field boundary..... 62

Equation 3-18 – Magnetic antenna factor..... 65

Equation 3-19 – Impedance of free space..... 66

Equation 4-1 – Total uncertainty from m contributions 91

Equation 4-2 – Derivation of voltage from power (in dBm) and impedance111

Equation 4-3 – Conversion of P(dBm) to P(W).....	112
Equation 4-4 – Conversion of dB μ V to V.....	149

CONSTANTS

The following constants have been assumed throughout this thesis

Name	Symbol	Constant Value
Speed of light in a vacuum	c	299 792 458 m/s
Permeability of a vacuum	μ_0	$4\pi \times 10^{-7}$ H/m
Permittivity of a vacuum	ϵ_0	$8.854187817 \times 10^{-12}$ F/m

CHAPTER 1 - BACKGROUND

1.1 HISTORY OF POWERLINE TELECOMMUNICATION

Powerline Telecommunications (PLT), sometimes also referred to as Powerline Communications (PLC) or Broadband over Powerline (BPL) is a development of a technology that has been in existence for over a century. PLT is a technology that uses the electrical distribution network as a medium for communicating information. An early example is the registration of a patent by Swiss inventors Routin and Brown for the control of street lighting using PLT (Routin and Brown 1897). Throughout the twentieth century various adaptations of control techniques had been researched, however a significant change in impetus occurred with the deregulation of the public utilities. In the early nineties deregulation of the public utilities led to significant interest by electrical distribution companies looking to increase profit margins by exploiting alternative technologies. Using the electrical distribution network as a communications medium was initially researched to provide data and control for the benefit of the electrical distribution companies - for example automatic meter reading. These technologies led to the development of a number of different bandwidth possibilities that could be sold as a service to its customers, or used by the providers themselves to make more efficient use of power consumption and generation. The same interest was experienced across the United States of America and Asia.

1.2 POWERLINE TELECOMMUNICATION

A detailed explanation of PLT and the electrical network is given in chapter 3, however the following paragraphs define some terminology that will be required to fully understand chapter 2.

Whilst it is possible to send PLT data across the entire network, trials in the UK have concentrated on servicing the 240V section (also known as the “last mile”). Although it is possible to send data across the high voltage network it is more likely that a high capacity data link would be connected to the 11kV sub-stations using conventional high data rate cabling such as fibre optic or co-axial.

1.2.1 Low frequency PLT

Because the control and telemetry of elements of a distribution system, (e.g automatic meter reading) occur relatively infrequently and do not require complex messages to be transmitted, there is no requirement for a high bandwidth system. The development and subsequent regulation of “low frequency” PLT (sometimes known as narrowband PLT) has resulted in systems that operate from 3kHz – 148.5kHz under European Standard EN 50065–7.

1.2.2 High frequency PLT

With the advent of home internet connectivity in the 1990's and the increasing advances in video streaming, the numbers of both personal and commercial users of data services have increased to unpredicted levels. PLT allows data transmission to premises and has the potential to match the data rates offered by both telephone and cable companies. To achieve the required data rates, higher frequencies are required. In 2011 the proposed frequency band for high frequency PLT (sometimes known as broadband PLT) in the EU is 1.6MHz – 30MHz, although PLT systems that operate at frequencies up to 500MHz and possibly beyond (known as gigaband PLT) are being developed.

1.2.3 Access PLT

The cabling that runs from an 11kV sub-station to the user premises is known as the access system. The access system could allow electrical distribution companies to act as data service providers.

1.2.4 In House PLT

The cabling that runs from the customer's consumer unit to each electrical outlet within a property is known as the in-house system. This is controlled by the customer and could be used to set up room to room data communications. To avoid interference, access and in-house systems are allocated a different sub-band of frequencies within the 1.6MHz - 30MHz band. For example in the EU the access band is 1.6MHz – 9.9MHz and the in-house band is 10MHz – 30MHz (ETSI 2001), although as indicated previously other countries are investigating higher bandwidth options.

1.3 POTENTIAL PLT APPLICATIONS

Initially, low frequency PLT was mainly used by power distribution companies for control of their equipment. In recent years however low frequency PLT has found limited use in providing low data rate intra-building networking and may facilitate the "Smart Grid" in the future. Examples are audio baby monitors connected between rooms, normally in a simplex configuration and home automation using the X10 standard to allow remote control of electrical appliances such as lighting. It is however high frequency PLT that offers the greatest potential for exploitation. The following paragraphs provide an insight into the potential uses of high frequency PLT and demonstrate why there is such excitement in this research area.

1.3.1 Broadband internet access

Since distribution companies control their own power networks, the obvious market to migrate to is as a provider of internet services. Whilst most UK users have access to broadband via cable and telephone networks, the costs are still relatively high due to the initial cost of new infrastructure. Cable providers tend to only run their networks in densely populated areas where the cost per user can be kept financially competitive. Telephone companies providing Asymmetric Digital Subscriber Lines

(ADSL) are also limited by the proximity of the end user to an exchange. It is these limitations that make PLT attractive to rural or geographically distributed communities. Since the user already has an electrical network connection, many users can be connected by high-speed data to their local electrical sub-station. In developing countries where there is a limited telephone network, PLT may offer an affordable solution to the "digital divide" (Digital Divide Institute 2011)

1.3.2 Intra-building networking

The major use for intra-building PLT is for home and office networking of data. Currently this is designed to the IEEE 802.11 wireless standard. PLT provides the benefit that no additional router is required since all control information can be managed within a standard PLT modem. The disadvantage is that the user has to be within proximity of an electrical outlet and therefore use in a garden is likely to be precluded unless an electrical extension cable is run.

1.3.3 Video streaming

As well as running normal terrestrial TV programmes, cable network providers offer specialist channels such as sport and movies. These facilities are available at a time convenient to the user and are not constrained by a TV schedule. They can also offer user demanded replay of programmes already shown - a free video recording service in some respects. Some also allow the pausing and rewinding of live broadcasts of both video and radio. PLT operators are looking to move into this market because it allows them to provide a service using their existing networks. In addition, users can watch any TV in the house without the constraint of a dedicated cable point.

1.4 INTEROPERABILITY

For PLT to be regulated for use it has one major hurdle to overcome, which is the ability to coexist with other services that use the electromagnetic spectrum. The

current PLT frequency allocation for the EU (1.6MHz – 30MHz) overlaps the High Frequency (HF) radio spectrum used for communications by the military, radio amateurs, maritime, aeronautical and broadcasters to name but a few; the latter being of particular interest as digital services roll out.

1.4.1 Radiated emissions

The major disadvantage that PLT has is that the communication channel, i.e. the mains distribution network, is not well matched to the data source (PLT modem/server). For example, a cable TV company creates an infrastructure that uses 75 Ω cables to match to 75 Ω transmitters and receivers. The result is that the losses introduced between the transmitter and a user's premises are negligible with the exception of any cable junctions. These junctions are well characterised and therefore a loss budget can be calculated to guarantee a level of service to the user. PLT on the other hand has the disadvantage that the mains network was not designed for communications in the 1.6MHz – 30MHz band and therefore the distribution system is different for premises around the UK and in different countries around the world. This problem is compounded by the fact that the users premises may be modified by the user through the addition of electrical sockets and lighting circuits. In essence the actual network is dynamic because as users add appliances to the network (for example switching on kettles or televisions) there is an effect on the network impedance and hence a mismatch to the data source. This impedance mismatch results in a radiated electromagnetic field that has interference effects on electrical equipment at some distance from the PLT system. A detailed explanation of the interference mechanism is given in chapter 3.

1.4.2 Cumulative emission

If indeed PLT does affect other services, one of the concerns is that a significant roll out would have the cumulative effect of raising the overall electromagnetic

background noise level in the HF band. Predictions have been made by various authors (Flintoft, McCormack and Papatsoris 2000) and (Stott 2001a) which could have a detrimental effect on the ability to communicate by radio in the HF band. These studies will be discussed in detail in chapter 2.

1.4.3 Conducted emission/susceptibility

Whilst it may appear that conducted emissions could also affect users connected to the powerline, it is not as critical as it first appears. The rationale for this is that Electromagnetic Compatibility (EMC) standards that set limits for conducted emissions and susceptibility are already in place. The question may be asked "why not amend these standards to include radiated emissions?" The answer to this question has been the topic of much research over the last 10 years and is the main topic which will be discussed in this thesis.

1.5 REGULATION

1.5.1 Background

Regulation of telecommunications is managed primarily at a national level under legislation passed by a national government. For a system operator to be able to provide a telecommunication service, they are required to be licensed to ensure interoperability with other services. Since many of these services are radio based the allocation of frequency bands cannot be constrained within the geographical boundaries of a country. The allocation of the frequency spectrum is therefore promoted at an international level by the International Telecommunication Union (ITU). Within the EU, frequency spectrum management is co-ordinated by the Conference of European Post and Telecommunication Administrations (CEPT).

1.5.2 National (UK)

Within the UK the licensing of telecommunication services is the responsibility of the Office of Communications (OfCom). The two primary pieces of legislation that are

used are the "Wireless Telegraphy Act (1949)" for radio and the "Telecommunication Act (1984)" for telecommunications irrespective of the medium used. It is the role of OfCom to licence operators and investigate complaints when non-compliance (e.g interference) is reported.

1.5.3 EU

Within the EU, CEPT control the Electronic Communication Committee (ECC) which is responsible for agreeing regulations including protection criteria. These are issued as standards which are produced by the European Telecommunication Institute (ETSI) for telecommunication equipment and the European Committee for Electrotechnical Standardisation (CENELEC) for electrical/electronic equipment.

1.5.4 International

At an international level there is no specific regulation, although as discussed above the ITU promote global communication standardisation to assist member states with compatibility.

1.6 ELECTROMAGNETIC COMPATIBILITY (EMC) STANDARDS AND ENFORCEMENT

1.6.1 EMC

EMC is a systems approach ensuring that different equipment can co-exist without affecting each other by way of their emission or susceptibility to electromagnetic fields. EMC is managed through standardisation and can either be at a national or international level. Within a single nation there are many standardisation bodies depending upon the environment. For example there are EMC standards that are specific to the military, to the automotive industry and to the medical industry.

An obvious example of incompatibility is when a hairdryer operates and the picture on a traditional cathode ray tube television screen deteriorates. This is caused both by radiated electromagnetic energy through space and also conducted energy along

the mains cable. At the same time the television is said to be susceptible to both radiation and conduction as shown in Figure 1-1.

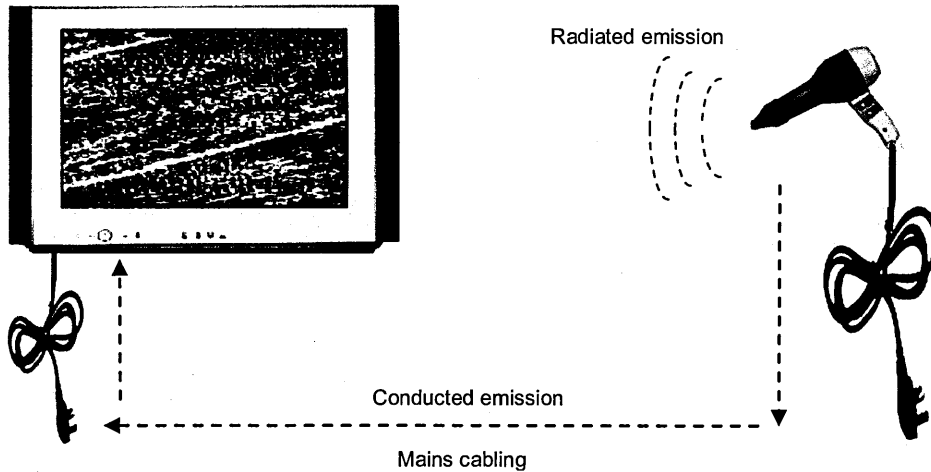


Figure 1-1 – EMC interference paths

1.6.2 National Standards

Nationally, the UK EMC standard applicable to PLT is BS EN 55022:2006. BS EN 55022 is derived from CISPR 22:2006 and sets limits for conducted emissions from 150kHz to 30 MHz but has no radiated limits. As will be seen in chapter 2, attempts have been made to derive equivalent radiated limits but there is contention of their validity by many authors. Before it was rescinded, OfCom used an enforcement standard MPT1570 (January 2003) if a complaint was made, but this only covered the frequency range 9kHz -1.6MHz. A draft variant covering 1.6MHz – 30MHz was circulated for comment but never formally issued, because an EU wide EMC compliance standard was perceived to be imminent.

1.6.3 EU Standards

The EU EMC compliance standard EN 55022:2006 is the European parent standard of BS EN 55022. It was published and subsequently updated as a result of EMC directives 89/336/EEC and 2004/108/EC (European Union 2004) which set compliance limits for electrical/electronic equipment manufacturers marketing products in the EU. Compliance entitles the product to contain the CE mark. A range

of EMC standards exist covering medical, automotive, maritime among others and will be discussed in chapter 3. Within the EU there is central direction to harmonise the EMC standards applicable to wired telecommunications (European Union 2001).

1.6.4 International Standards

International EMC standards are rationalised under the auspices of the International Electrotechnical Committee (IEC) by way of the International Special Committee on Radio Interference (CISPR). In the case of PLT, CISPR 22 is the top level standard and in common with BS EN 55022 has been under review for many years to cover radiated emissions in the PLT band. As well as international standards, there are overseas national standards that have a significant impact on marketing EMC compliant products. An example is the Federal Communications Commission (FCC) part 15 (Sep 05) standard for items sold in the United States of America.

1.7 EVIDENCE TO SATISFY REQUIREMENTS

There is currently no EMC compliance standard that covers the frequency range of HF PLT with respect to radiated emissions that can be used with a high degree of repeatability. EMC testing is typically conducted in a shielded room or on an Open Area Test Site (OATS) where there is an installed ground plane and the attenuation factor of the site is known. PLT measurements on the other hand are taken in-situ where a repeatable test set-up is difficult to achieve.

Ideally PLT modem manufacturers would test conducted emissions for their PLT modem and this would be sufficient to provide compatibility under normal usage. However as the impedance of the electrical network is both variable and dynamic, determination of an acceptable conduction level is difficult. There is an increased amount of global activity and various methodologies have been undertaken in pursuit of a standard compliance limit. These are discussed below:

1.7.1 Theoretical prediction

Theoretical predictions have been made by many authors and will be discussed in depth in chapter 2. The rationale is as follows. A power level of x mW is injected into a mains network. Based upon predicted impedance, a portion of the injected signal will radiate or be induced into the surrounding area. This electromagnetic field will propagate through space attenuated by the reciprocal of distance until it reaches a remote receiver. If the electric field value at the receiver is greater than its signal to noise ratio then interference will occur. There are significant errors that are not accounted for in this method and these will be discussed in chapter 2.

1.7.2 Modelling

It is possible to model electromagnetic systems using electromagnetic modelling software. Most software is based upon the Numerical Electromagnetic Code 2 (NEC2) engine developed by the US Navy circa 1981. Care however has to be taken to understand the method that NEC2 uses to predict radiation. The tool is primarily used to predict radiation from antenna systems where the source and receiver are physically far apart with respect to the wavelength and source dimensions. Additionally it is designed for antenna structures that are reasonably easy to model because they consist of loops and straight lines. The modelling of PLT coupling is primarily concerned with dimensions less than that of the source structure and certainly less than the operating wavelength of high frequency PLT. Whilst NEC2 is still accurate at these dimensions, care needs to be taken when creating a representative model to minimise potential calculation errors.

1.7.3 Measurement

The obvious method of detailing the electromagnetic field strength that is present at a victim receiver is to measure it. There are however complexities in the

measurement technique that mean that the true value of the electromagnetic field is extremely difficult to determine. The detail of this will be discussed in chapter 3.

1.8 THESIS OUTLINE

The structure of this thesis is as follows:

1.8.1 Chapter 1 - Background

Chapter 1 (this chapter) sets the background to PLT and the current work being undertaken to allow PLT to become licensed for use at high frequencies.

1.8.2 Chapter 2 – Existing Research in HF Powerline Communication

Chapter 2 discusses in detail the work undertaken by other researchers and commercial organisations in the PLT field. It attempts to demonstrate the different methods that others have taken and critically identifies the limitations in these methods.

1.8.3 Chapter 3 – Theory of EMC and PLT

Chapter 3 covers the theory of PLT and EMC and provides more detail as to why traditional EMC methods are difficult to apply to PLT.

1.8.4 Chapter 4 - Measurements

Chapter 4 details a range of PLT measurements made by the Power Systems Communications Research Group (PSCRG) at the Open University. The group have had access to PLT test sites and the measurements taken are novel in this field. This will include mutual interference testing which is a method developed to overcome the difficulty in determining a “safe limit”.

1.8.5 Chapter 5 – Summary of Results

Chapter 5 provides an analysis of the measurement results and introduces non-engineering aspects that will have an effect on the roll-out of PLT and the eventual agreed limit and measurement standard.

1.8.6 Chapter 6 – Other Factors, Conclusion and Further Work

Chapter 6 is a conclusion of the research and makes recommendations of where further research could be directed by other groups.

1.9 CONCLUSION

PLT is an emerging technology that allows electrical distribution companies to offer a competitive broadband service using its existing network. Because the electrical network is not ideal for transmission in the PLT frequency band, electromagnetic radiation occurs. The level of radiation is a concern to users of other services and research is being undertaken globally to determine an acceptable level of radiation. This research has, to date, taken the form of theoretical prediction, computer modelling and actual measurements. The aim of this thesis is to present a balanced view of the possible methods of arriving at an “acceptable” radiated emissions level. Where this is not possible an attempt will be made to recommend a measurement methodology that is repeatable and provides a balance between powerline service delivery and an acceptable protection of services. Chapter 2 discusses in detail the work done by others in the field and how traditional methods to date have not led to standardisation due to the issues and complexities of measuring the radiated emissions from PLT.

CHAPTER 2 - EXISTING RESEARCH IN HF POWERLINE COMMUNICATION

The previous chapter explained what PLT is and the opportunities that it could potentially bring as a bearer network for data services. It further described the issue of how it might be regulated and the difficulty involved in agreeing EMC standards that allow modem manufacturers to produce products and powerline companies to comply with distributed system regulations. This chapter discusses the work undertaken to date to determine EMC limits using the different methodologies discussed in chapter 1 - theoretical prediction, modelling and measurement.

2.1 THEORETICAL PREDICTION

When the concept of increasing the bandwidth of PLT was first discussed in the early 1990's, there was a general opinion that it would affect other services in the high frequency band, albeit this was not supported by evidence. Research groups initially attempted to demonstrate this theoretically by using predictions based upon electromagnetic, radio and EMC theories - the general principal being that an unwanted electric field generated by a PLT system would have a certain electric or magnetic field strength. This would propagate through space and be attenuated by some factor, dependant on the local environment and arrive at a victim system (e.g. a radio receiver). At the victim receiver, if the electric field strength was sufficiently large at the frequency of interest it would affect the reception of any wanted signal due to the ratio of the intended signal to the interfering one. This chapter discusses the most significant papers that have used the theoretical prediction methodology and critically analyses the associated results.

2.1.1 Electronic Communications Committee of CEPT Report (May 2003)

CEPT, as the responsible body in the EU for spectrum management were concerned in 1999 when the UK presented information of a PLT trial by NOR.WEB in Manchester

that had potential to interfere with radio services. A working group was set up to report on the effects PLT may have on radio systems. The final report (ECC 2003) was the first attempt to comprehensively predict what the effect on other services due to PLT could be. The methodology employed was to baseline interference by referring it to a signal to noise ratio. Firstly the background noise values of ITU-R372-7 were used as representative of a generic urban installation. Secondly five examples are provided based upon proposed emission limits as a worst case compliant system. From these emission values a separation distance between a “compliant” PLT system and victim receiver was predicted based upon an electric field attenuation using a 1/distance (defined as 1/r) attenuation factor. The underlying assumption is that the signal to noise ratio should not be degraded by more than 0.5dB. A range of predictions were given depending upon the environment and these are reproduced in Table 2-1.

		1.5 MHz quiet rural	30 MHz quiet rural	1.5 MHz business	30 MHz business
Proposed German NB30 limit		920 m	320 m	63 m	52 m
Proposed Norway limit		94 m	39 m	0 m	6 m
Proposed UK MPT1570 limit		770 m	Not applicable	53 m	Not applicable
Proposed BBC limit		38 m	15 m	0 m	2 m
FCC part 15 limit		35 km	46 km	2,4 km	7,4 km

Table 2-1 – Separation required to ensure S/N ratio is not degraded by less than 0.5dB.

Table 2-1 demonstrates that the separation distance is dependent on which protection limit is chosen as a safe emitted radiation limit and also that the estimated range is highly variable. The report concluded that a common standard emission limit should be set for PLT.

2.1.2 Reports by researchers

Various researchers have used a similar methodology to the CEPT report, and similar results have been produced. Two papers of particular interest (Stott 1999) and (Stott 2001a) discuss the possible effect on radio receivers due to the cumulative effect of a

mass roll out of PLT. It is argued mathematically that ground wave propagation is the greatest threat to radio receiving sites and that the sky wave mode may require a separation distance of up to 100km in order to afford the protection laid out in MPT1570. Furthermore it is argued that as well as effects on receiver sites there may well be effects on distant objects, particularly aircraft, due to sky-wave propagation. Whilst it is difficult to obtain definitive information, there does not appear to have been any complaints from aircraft since these papers were produced in 1999/2001. This is probably due to a number of factors. Firstly aircraft operate on VHF air traffic control frequencies when transiting mainland in accordance with flying regulations. Secondly the HF radio system would only be used on long haul flights when out of reach of urban conurbations and the radiated field at these distances would be insignificant. Thirdly most modern aircraft use Super High Frequency (SHF) satellite communication rather than HF communications for beyond line of sight communications. Finally, there has not been a mass roll out of PLT systems to cause a significant effect.

A similar theoretical study (Price 2002), used an emission level that was a proposed limit in Germany, known as NB30 and assumed that PLT roll out would be constant across the UK. The study is presented geographically, however many of the assumptions are worst case and when considered together are not weighted accordingly. For example it assumes that the emission will occur across the whole of the UK and that the receiver will be within 1m of the PLT network. Furthermore it assumes that the receiver could not be moved to a different location. In fact since this report was written many users now receive the radio broadcast in question via digital freeview or across the internet, therefore if PLT was rolled out across the UK the affects are not likely to be as significant as presented.

2.1.3 Using ITU-R Noise Limits

An early prediction, and one that is favoured by radio amateurs (Stott 2001b), uses “ITU-R P.372” as a basis for setting a maximum limit of noise at the antenna of a victim receiver. As the paper was written circa 2001 it refers ITU-R P.372-7, which was then the latest revision (the currently approved revision is ITU-R P.372-9, 2007), although the changes are not significant. The basis of ITU-R P.372 is that it defines graphs for manmade noise in the HF spectrum for a number of locations, namely, quiet rural, rural, residential and business. The difference between business and quiet rural is approximately 25dB. Stott (2001b) claims that a representative location for a HF radio amateur is a quiet rural/rural environment and further defines a new averaged noise curve to represent a user in a rural/quiet rural location. A claim is made that an increase of 0.5dB would be the maximum acceptable and therefore any increase in noise floor due to a PLT system would be unacceptable. A representative distance of 10m is used as the distance between an interfering PLT cable and the antenna of a receiver. It is claimed that at 10m the noise level is too low for EMC measurement systems and therefore measurement should be undertaken at 1m and extrapolated to 10m using a $1/r$ attenuation coefficient. Using this methodology, Stott proposes a measurement distance of 1m between 150kHz – 30 MHz and the following limits. H is the magnetic field strength in Amperes/metre and E is the electric field strength in Volts/metre (represented here in decibels):

Magnetic field strength,

$$H(\text{dB}\mu\text{A}/\text{m in 9kHz peak}) = -29.7 - 8.15\text{Log}_{10}(f / \text{MHz}) \quad (2-1)$$

Electric field strength,

$$E(\text{dB}\mu\text{V}/\text{m in 9kHz peak}) = 21.8 - 8.15\text{Log}_{10}(f / \text{MHz}) \quad (2-2)$$

2.1.4 Conversion of CISPR 22 (EN 55022) conduction limits to radiated limits

The methodology of using a signal to noise ratio to determine the likely interference is often complicated by the presentation of emissions. For example an intended signal x V/m injected into a receiver that is also receiving noise of y V/m will result in a signal to noise ratio of x/y (as a direct ratio). However the derivation of y is often based on a limit that would be acceptable as an EMC product standard. The most commonly used standard is CISPR 22 which sets limits for the conducted emission out of a communications port and not a radiated emission from that port connected to a typical network. In order for a signal to noise ratio to be used attempts have been made (N-sine 2000) and (Brannon 2005) to convert this conducted emission into a radiated emission. A factor known as the K-Factor has been derived. The K-Factor is analogous to the antenna factor in EMC measurements in that it relates the measured Electric field at a set distance to the Voltage injected into the terminals (Equations 2-3, 2-4 and 2-5 below):

$$\text{K Factor}(\text{1/m}) = \frac{E(\text{V/m})}{V(\text{V})} \quad (2-3)$$

$$\text{K Factor}(\text{dB/m}) = 20\log(E(\mu\text{V/m})) - 20\log V(\mu\text{V}) \quad (2-4)$$

$$\text{K Factor}(\text{dB/m}) = E(\text{dB}\mu\text{V/m}) - V(\text{dB}\mu\text{V}) \quad (2-5)$$

It should be noted that the use of K-Factor as a measurement technique requires an indicative impedance to be used. As discussed in chapter 1, the mains impedance is not-standardised and is dynamic in nature and therefore the indicative impedance may be significantly different to the actual impedance.

As K-Factor is specific to a measurement distance it should be applied at that distance only. In general EMC measurements, an antenna factor is often expressed as the “far-field” antenna factor and therefore can be applied at any distance beyond the distance it was calibrated at, adjusted by a far-field attenuation factor. This assumes that the signal being measured is in the far-field and is the case for most Equipment Under Test (EUT) where their dimensions are small and the frequency high in comparison to the distance. This is not true for PLT systems as a 10m measurement of a distributed mains system would be in the near-field. If the K-Factor is to be correctly used it should therefore be subject to error calculations. Furthermore the antenna factor of an EMC antenna will always be used on an OATS which has a reliable ground plane and where calibration of the attenuation with distance is known. This is not the case in PLT measurements and will be discussed in depth later in the chapter. Furthermore there is no standard definition of measurement bandwidth, antenna polarisation or detector setting (peak/quasi-peak/average) therefore any quoted value of K-Factor must be used with caution when attempting to predict the radiated affect on a victim receiver.

2.1.5 Attenuation with distance

As part of the rationale that a field measured at one distance will affect a receiver at another distance it is necessary to understand the attenuation of radiated field strength with distance. It is claimed (Stott 2003) that the attenuation with distance of $1/r$ is a good approximation for PLT systems. However, there is some contention with this theoretical prediction as will be discussed in Chapter 3. Furthermore, Dostert, 2003 reiterates attenuation with $1/r$ but states that this has limits observed below 6MHz and at a measurement distance of 3m. As this is fundamental to the effects of PLT in other systems, further measurements will be discussed in Chapter 4 that will aim to verify work by previous authors. The prominent piece of theoretical work in this area (Guellemann 1978) attempted to recognise the proliferation of magnetic generation equipment into the market place by updating the German EMC regulation standards.

He stated that all measurements should be taken in the far-field but recognised that this would lead to a measurement distance of up to 100m. He recommended a measurement distance of 100m (Class A) and 30m (Class B) and suggested that below 30MHz the attenuation with distance extrapolation factor should be 31.5dB rather than 20dB, but conceded that 20dB above 30MHz was acceptable. This was correlated with a signal strength of an intentional transmitter at an in-house receiver of 1mV/m (60dBµV/m) and led to the often quoted "Guellemann limit"

2.1.6 Cumulative effects

A final complexity that some authors have attempted to predict is the effect of a mass roll out of PLT. All of the assessments above seek to predict the radiated emissions from a single point source, wire or loop. A concern by those likely to be affected by PLT is the cumulative effect of multiple access networks. Stott, 2001a, through geometric analysis demonstrated the theoretical cumulative effects for both airborne and ground based receivers. The conclusion of the study is that aircraft would be significantly affected by a mass roll out over the European continent. The author further goes on to demonstrate that the effects are not always dependant on height as the increase in additional PLT systems viewed by an airborne receiver in part cancels the attenuation of the radiated interference. The study also concludes that ground receivers are not significantly affected by a mass roll out of PLT. However, only access systems were considered and the local effects of multiple in-house systems were not analysed.

2.1.7 Summary of theoretical prediction

In general, theoretical prediction was the main method used in the late nineties when PLT was first being developed and there were no systems available to measure or make a technical assessment against. The analyses were primarily undertaken by organisations that would likely be affected by any mass roll out of PLT (radio amateurs, broadcasters, regulatory bodies) and therefore many of the predictions used worst

case estimations. None of the papers presented estimation errors, but quoted figures to an accuracy of 1 decimal point and therefore their use in prediction should only be used as an indicator of possible interference.

2.2 MODELLING

An alternative to theoretical prediction of PLT Radiation is to set up models that aim to replicate the access or in-house elements of a PLT system. Modelling is not prevalent and as with theoretical prediction, caution is required when quoting figures from modelled systems.

2.2.1 Smith's Report for the RA

An early model (Womersley, Simmons and Tournadre 1998), known as the Advanced DSL and PLT Prediction Tool (ADAPPT), was created with the following objectives:

- it should predict the maximum and likely variability of both E and H fields produced in a variety of locations around the system under consideration.
- the model should work for frequencies from 300 kHz to 3 GHz. (For generality, the model developed actually spans the range of frequencies from 30 kHz to 3 GHz, and allows a bandwidth in the range from 0.1kHz to 1000kHz to be individually specified for both the transmitted signal and the receiver response).
- the launch power, frequency and impedance should be adjustable.

This model was novel in that it aimed to predict re-radiation from street furniture such as lampposts. It is also well based as it is one of the few models that undertook field measurements to validate the model. The conclusion was that when measuring typical PLT radiation (25 – 80 dB μ V/m) the error was approximately 15dB μ V/m.

2.2.2 NTIA Report 04-413

NTIA, 2004 was the first major study to use the NEC2 software to model a powerline network. The NTIA report analyses the access network and therefore the long lengths

of overhead power cabling can be modelled accurately, taking into account the proximity to the ground. NTIA, further backed this modelling up by a measurement campaign to test the validity of their model. The results show a strong correlation between the modelled and measured values. It also demonstrated that the attenuation with distance was not always $1/r$ as predicted from a point source and therefore adds weight to some arguments that BPL signals act as far-field propagators further than 2 or 3 m from the source. The main benefit that NEC offers is that it can predict effects in both the near and far field. The implications of this are further discussed in chapter 3.

2.2.3 American Radio Relay League (ARRL) Models

The only other models identified were produced by the ARRL (ARRL 2002). The models were fairly rudimentary, produced using NEC2 and aimed to show the typical comparison of PLT to an antenna. The modelled system consisted of two 300m lengths of unshielded conductor separated by 5m differentially fed at one end as a balanced transmission line. A balanced transmission line is one that has two identical conductors which have equal impedance along their lengths and equal impedance to ground. This is in contrast to an unbalanced transmission line such as a coaxial cable that has one conductor of a different type that is connected to earth. The model used the accepted impedance of 50Ω . The results showed that the modelled system equated to a gain of -6.0dBi at 3.5MHz and -7.8dBi at 14 MHz. This was not as large a gain as theoretically predicted by other authors but nevertheless demonstrates typical values that could be expected.

2.2.4 Summary of modelling

Although modelling should offer a better understanding of the likely effects on receivers from PLT interference, surprisingly few researchers have adopted it as a technique. The main reason is that it only lends itself to highly idealised and symmetrical models, unless the researcher is prepared to invest substantial time and effort in understanding

the constraints of NEC2 and obtaining access to high power computing. The models presented here are typical of work by others in that they cover access band PLT only. To date no researcher has modelled an in-house system.

2.3 MEASUREMENT

2.3.1 Measurements in context

At the time of the measurement campaigns that will be discussed below (2002 – present) it is worth putting in context the difficulties faced by researchers. There were no operational networks worldwide that could be used for measurement and hence many researchers relied upon theoretical prediction and modelling. A few unrepresentative test sites could be found across Europe, but these were small in size and scope. Equally, PLT modem manufacture was at an early stage and did not employ any type of filtering to protect amateur radio bands and therefore power companies were nervous of releasing data that would provide them with a difficulty in public relations. On that basis, most researchers had no access to a live network to conduct actual measurements. As will be discussed in chapter 3, there was (and still is) great debate on how to undertake a representative and repeatable measurement of PLT radiated emissions. It should therefore be recognised, that as of 2002, measurement of PLT was contentious and that the roll out of large scale test sites in the UK was exciting but controversial for power companies, receiver operators and researchers.

2.3.2 OfCom (RA)

In 2005 the Radio-communications Agency (RA), now OfCom, undertook a measurement campaign across a range of test sites in the UK. The test sites were set up and sponsored by Scottish and Southern Energy PLC (SSE), a UK electrical energy provider. The sites had different PLT modem technologies and the aim was to investigate the radiated emissions using the MPT1570 (OfCom 2003) measurement

technique extrapolated to 30MHz. As has been explained in chapter 1, MPT1570 was an OfCom enforcement regulation covering the range 9kHz – 1.6MHz and had no formal authority above 1.6MHz. The following paragraphs summarise the conclusions of measurements at Crieff - DS2 system (OfCom 2005a), (OfCom 2002) Crieff - Amperion system (OfCom 2005b) and Winchester - ASCOM system (OfCom 2005c).

As there are no agreed limits it is difficult to compare radiated emission limits. For the remainder of this section the proposed German NB30 limit will be used as a baseline. It is a proposed enforcement limit that is midway between limits proposed by receiver operators and the US FCC Part 15 (the least demanding standard) and represents a fair limit for comparative purposes. Where possible all measurements have been extrapolated to 3m using an arbitrary 1/r attenuation factor.

2.3.3 DS2 system – Creiff, Scotland, UK

The DS2 system uses an Orthogonal Frequency Division Multiplexing (OFDM) carrier which in theory produces a lower level of interference and also accommodates severe channel conditions. The objectives of the tests were:

“1. To examine the DS2 PLT spectrum and characterise the notching capabilities provided by the chipset in order to assess its potential usefulness as an interference mitigation measure”.

“2. To measure the level of leakage emissions in the immediate vicinity of both the DS2 access PLT network and PLT customer premises”.

“3. To assess the effect of DS2 leakage emissions on short wave broadcast reception within the domestic environment”.

With respect to objective 1, OfCom concluded that the notches applied by DS2 did provide the claimed 20dB attenuation in the bands in question without significant degradation in operational performance. In the models under test notching was only available in the downstream direction. OfCom further concluded that notches to provide 30dB of attenuation were successful but probably provided an unacceptable degradation in performance. In the 2005 timeframe, the idea of notching was being presented as a method of protecting services whilst operating carriers that would have traditionally been above the national enforcement limit.

Regarding objective 2, OfCom noted that the launch power claimed by DS2 was assessed to be correct (-62dBm/Hz) which was a substantial improvement of 12dB over previous generations. The radiation from a PLT modem is proportional to the launch power, however a higher launch power is required to provide a guaranteed level of service to customers further from the source modem.

With respect to objective 3, OfCom noted that the measured field strength at 3m in dBµV/m was generally around the German NB30 limit, although parts of the band were as much as 15dBµV/m above NB30 at specific frequencies.

2.3.4 Main.net system – Creiff, Scotland, UK

The Main.net system used a Direct Sequence Spread Spectrum (DSSS) that in theory has the benefit of a lower average power than OFDM. The objective of the test was:

“Monitor the HF band in the vicinity of PLT cables”

No firm conclusions were drawn from the test as the report presented only the results of locations and measurement values. An analysis of the values is difficult to make as no measurement distance has been quoted, however the author does present a

comparison of the background noise to the PLT signal. In general the PLT signal was 5-10dB μ V/m over the noise floor, which itself was greater than the proposed NB30 limit.

2.3.5 ASCOM system – Winchester, England, UK

The ASCOM system uses 2MHz wide Gaussian Minimum Shift Keying (GMSK) carriers. GMSK is a form of modulation used in a variety of digital radio communications systems that attempts to overcome a problem with some forms of phase shift keying in that the sidebands extend outwards from the main carrier and can cause interference to other radio communications channels. The objectives of the tests were:

“1. To measure the level of leakage emissions at defined distances from the Ascom PLT network”.

“2. To assess the rate at which PLT leakage emissions regress as the distance from the network to the measurement position is increased”.

With respect to objective 1, with the modem set to operate at its full power setting of +8dBm per GMSK carrier (a Power Spectral Density (PSD) of -50dBm/Hz) emissions in the access band, measured at 3 metres from the substation, reached peaks of 50dB μ V/m which exceeds the NB30 emission limit by up to 15dB μ V/m.

Regarding objective 2, the rate at which PLT emissions reduce in level (regress) as the distance from the network is increased was measured at 1m, 3m, 10m, 30m and 100m distances. It was observed that emissions from the access network demonstrated a regression rate of approximately 20 dB per decade of distance (1/r).

2.3.6 Amperion system – Creiff, Scotland, UK

The Amperion roll out was significantly different to the other systems because it was designed for the US market as an access system using the 11kV overhead network. No roll out of equipment had been undertaken in the UK and as far as the author is aware in Europe at that time. The Amperion modems employed an OFDM signal architecture built around the DS2 chipset. The OFDM signal comprises 1280 carriers with 1.1 kHz spacing. In this instance the downstream spectrum has 768 carriers and occupies a 3.75 MHz bandwidth. The upstream spectrum comprises 512 carriers with a 2.75 MHz bandwidth. The Crieff network comprises 6 units; one at each end of the 2.3 km line and 4 repeater units.

The objective of the measurement campaign was:

- 1. To measure the level of radio frequency leakage emissions in the immediate vicinity of S&SE's Amperion enabled 11kV overhead PLT network using methods similar to those originally proposed in FCC 04-29 and confirmed in FCC 04-245*
- 2. At frequencies below 30 MHz, to measure both the magnetic and electric field in the immediate vicinity of S&SE's Amperion enabled 11kV overhead PLT network and establish the correlation between the two measurements.*
- 3. To assess the rate at which both the magnetic and electric field leakage emissions from the 11kV overhead line regress as the measurement distance is increased from 1 to 30 metres.*

4. To measure both magnetic and electric field leakage emissions at defined distances away from the 11kV overhead network until the emission levels fall to the noise floor of the measuring system

5. To characterise the Amperion PLT spectrum and measure the depth of the notches that can be applied.

With respect to objective 1, the Amperion equipment, operating with a launch PSD of -50dBm/Hz, produced a maximum electric field strength of 60dB μ V/m below 30MHz and 59dB μ V/m above 30MHz. These levels exceed the FCC Part 15 compliance limits by up to 8dB μ V/m below 30MHz and 27dB μ V/m above 30MHz. Although the report did not analyse at 3m, it is estimated that this would be some 30 – 40dB μ V/m above the NB30 limit.

Regarding objective 2, the downstream PLT spectrum produced a maximum difference between the Electric and Magnetic Field strengths of 8dB μ V/m for the magnetic field, occurring at half a wavelength along the line from the launch point.

In regard to objectives 3 and 4, below 30MHz the magnetic field regression, measured at 10m, 30m, 100m and 300m metres from the overhead line, was approximately 27dB/decade. The electric field regression varied between approximately 16 and 21dB/decade which is indicative of a $1/r$ regression for the electric field. Above 30MHz the electric field regression, measured at 10m, 30m, 100m, 300m, 1000m and 3000m metres from the overhead line, varied between 10 and 20 dB/decade, which is indicative of a regression of between $1/\sqrt{r}$ and $1/r$.

Regarding objective 5, an assessment of various notches was made, which concluded that they were comparative to previous measurements of DS2 technologies. They

provide a useful mechanism in the downstream direction but as yet are not implemented in the upstream direction. An assessment of notches to reduce PLT noise to the standard noise floor was made, however as PLT noise is generally 30-40dB μ V/m and notches only reduce the signal by 20dB this could never be achieved unless 40dB notches can be developed.

2.3.7 British Broadcasting Corporation (BBC) reports

As well as the tests at Crieff noted above, a team from the research and development department of the BBC also conducted a similar set of tests as OfCom (BBC 2003) and (BBC 2005). They undertook measurements of the ASCOM, Main.net and DS2 based systems in the same configuration. They also attempted to subjectively assess whether the radiated emissions from a PLT system would actually affect a member of the public receiving radio in the PLT band. The results of radiated emission were, as expected, similar to the OfCom results. They further demonstrated that with a radio receiver the obvious interference of PLT could be detected at 1m and 3m. The BBC team also noted that there is substantial difficulty in attempting to undertake measurements due to a lack of repeatability and also due to the background noise in the local environment.

2.3.8 Global reports

In 2004 the developing PLT market started to become more prevalent outside Europe with test sites being created in the USA and Australia. In Australia a measurement campaign was undertaken by CISPR (CISPR 2007) to determine the effects of PLT against a proposed compromise standard it was developing, with the aim of encouraging modem manufacturers to employ notching of up to 45dB. Measurements were taken inside and at 10m outside of urban and rural properties. The conclusion was that the measured electric field strength was typically 20 – 50dB μ V/m above the ambient noise level measured as a maximum. The modem under test (Corinix AV200 access modem) was assessed as being compliant with the proposed

CISPR-I standard, although for comparison purposes it was above the NB30 limit.

In 2004 in the US, a measurement campaign (Metavox inc 2004) was undertaken to determine the radiated emissions from an overhead access PLT system to assess compliance with the US FCC part 15 rules. The modems in question were Main.net early generation un-notched devices and the measurement distance was 30m. The measured electric field strength was typically 35-50dB μ V/m. Extrapolated back to a standard 3m measurement distance the values would increase by approximately 10dB. This would be within the FCC part 15 limits but not within the NB30 limits.

2.3.9 Summary of Measurements

The fundamental aim of most measurements was to indicate to CISPR and the national regulatory authorities the level of radiated emissions of PLT that might become an acceptable enforcement limit. It should also be remembered that across the world there were very few operational networks that could be measured and compared because any networks were on a trial basis with a limited number of users. These networks employed modems with different modulation schemes, differed in national standards of electrical distribution system and also had different environments (rural, urban, apartment, house etc). In the same timeframe there was major opposition by the radio amateur community and from 2005 some modem manufacturers attempted to provide a workable solution by inserting notches or removing the radiated emission completely in some radio bands, making a common comparison difficult.

This is further confused by a non-standard measurement methodology in terms of measurement distance, equipment, environment and ambient noise. Researchers have used a range of measurement distances from 1m to 30m as the standard distance. They often attempt to normalise these to 3m using a $1/r$ attenuation factor however scientifically this is no better than a very rough estimation. In terms of equipment, researchers have used loop antennas in various orientations and some have taken an

RMS value of the orientations in the three physical planes. Where loops are used these are then converted from a magnetic field strength to an electric field strength using a far-field free space conversion factor that is scientifically accurate only in very specific conditions. The results are further confused by the ambient noise of the environment. Some researchers have presented their results in terms of the difference due to PLT above the ambient noise level and others have presented the actual measured limits including the ambient noise level.

In conclusion the method of attempting EMC measurements in a non-standard way, in a non-characterised environment will provide results that are prone to error. These errors could be as much as an estimated 20 – 30 dB μ V/m. The one common conclusion that can be drawn from the measurements in this chapter is that none of the researchers have attempted to state the inaccuracies in their measurements. They do however state within 1dB μ V/m the likely effect on services due to PLT. Another observation is that most researchers have either been regulatory bodies who would be looking to enforce protection to a radio service or a radio operator such as BBC, ARRL etc. There have been limited independent measurements to date and therefore the likelihood of coming to an agreed standardisation limit based on theory or measurement campaigns is unlikely in the near future.

Recognising the limitations above, the consensus of all measurement results was that PLT radiation was in general above the arbitrary NB30 limit that is used by researchers as a representative mid-point between ITU-R radio protection requirements and that of the US FCC part 15 limit. Whilst notching may provide protection to some services (primarily radio bands) PLT would be unlikely to comply with a general EMC limit set around NB30.

2.4 SUMMARY

This chapter has discussed work undertaken by others in an attempt to assess the effects of PLT on other services. Initially, this was in terms of theoretical prediction based on electromagnetic and communication theory and limited modelling. As test networks became available researchers undertook measurements of actual PLT systems and made claims to the effects of PLT on services. The results, however, contain significant errors that have not been articulated by the researchers. In order to put this in context, chapter 3 will present the theory of electromagnetic radiation and EMC and will explain in more detail some of the PLT technologies in order to demonstrate the limitations in work that has been presented to date by other authors.

CHAPTER 3 - THEORY OF EMC AND PLT

The previous chapter discussed work undertaken by others in terms of theoretical prediction, modelling and measurement. This chapter explains the PLT architecture and modulation schemes in more detail. It then explains electromagnetic radiation and how electromagnetic theory is applied to EMC standards in general and with respect to PLT. A thorough understanding of EMC theory is essential for the discussions in chapter 4 and to better understand the limitations in work done by others. Furthermore it is essential in the understanding of error calculation of EMC measurements when one tries to predict an acceptable radiation limit.

3.1 PLT

In order to understand PLT radiated emission it is first necessary to understand the architecture of PLT systems. The fundamental limitation of PLT as a communications system is that the PLT modem is not matched to the network as would be the case on a well designed communications channel. The network characteristic impedance is non-standard due to differences in wiring on route to and at a customer's premises and is dynamic in nature due to appliances being connected and disconnected to it.

3.1.1 The power network

PLT as a global technology has difficulties to overcome because the power network architectures of different countries have evolved over a century and regulations have been developed nationally. For example the networks in the EU aim to deliver a 230V, 50Hz feed to the domestic customer's premises. In the UK, the premises are also provided with an earth connection at each electrical socket and the domestic architecture is based on the "ring main" concept. In modern domestic premises the distribution will typically be subdivided from a 100A distribution unit into a number of circuits for mains wiring, lighting, heating, garage and external. Older premises may only have a single mains and lighting circuit and be protected by wire fuses rather than

residual current or earth leakage circuit breakers. This can be contrasted with the domestic setup in the USA where the electrical system is 120V/60Hz and is often supplied radially from the distribution panel. A further complication is that industrial supplies are typically offered in a three phase configuration with the neutral fed in either a star or delta configuration. Figure 3-1¹ demonstrates graphically the hierarchical structure of the United Kingdom electrical distribution network.

¹ Courtesy of UK National Grid

How electricity is made and transmitted

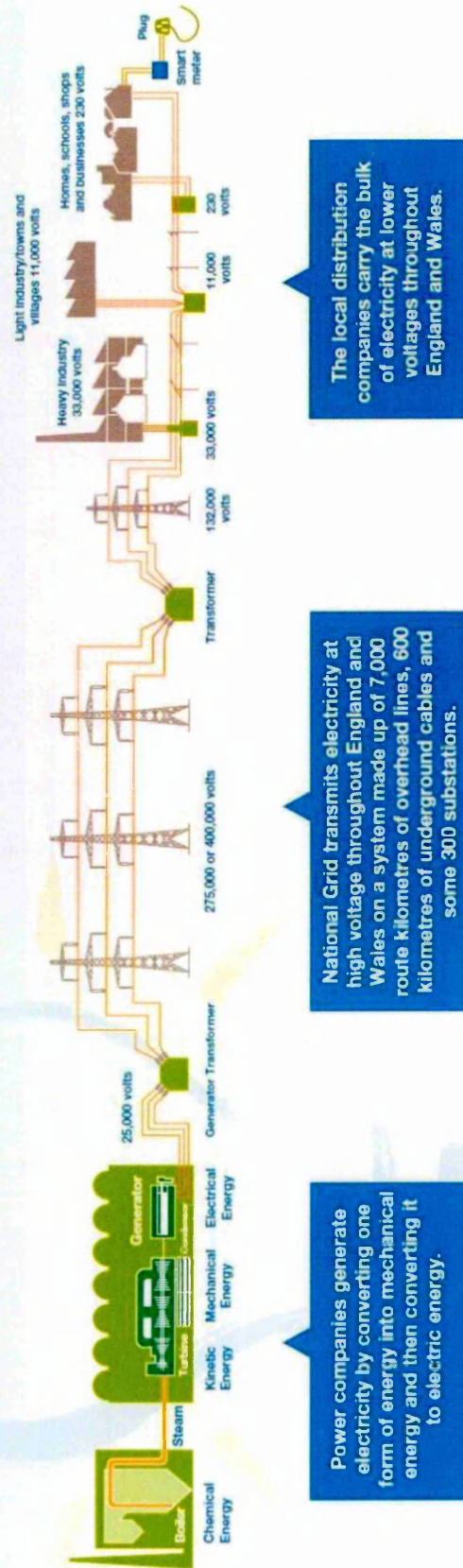


Figure 3-1 – UK electrical distribution network

3.1.2 Access/In-house

Since PLT signals can be transmitted from the substation to the end user, there is a likelihood that there will be interference between systems, particularly in densely populated urban areas. In the early days of PLT this led to a definition of the terms “access band” and “in-house band”. The access band is used for the network between the substation and the access point of the subscriber’s premises. This would be under the control of the local distribution company and would be used to send data to the user analogous to cable or xDSL. The in-house band is used for equipment that is owned and installed by the subscriber and is used to distribute PLT around the home, analogous to a traditional wireless network.

With respect to PLT there are two main methods of coexistence, namely contention based and collision free. With a contention based protocol such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), the node that wants to transmit waits a period of time before attempting to reserve the channel. If during this time, the node has not detected the channel being reserved by another node, it will reserve the channel by sending a control packet. Upon reception of the reservation packet, the receiver will communicate that it is free to receive data, or that the channel is busy. Contention based protocols tend to be simple to implement and robust, however they have lower data rates due to increased latencies with channel load, and do not offer any type of guarantees in the delivery of data. For that reason they are not used for high speed PLT.

There are various schemes that can be used to facilitate collision free coexistence of the access and in-house bands, but the three main schemes are:

- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- Hybrid of FDM/TDM

An FDM scheme allocates dedicated frequencies and bands for both access and in-house data transmission. There is no overlap between the bands and therefore transmission can take place simultaneously. In the early days of PLT, ETSI proposed a FDM scheme (Figure 3-2) where the access band would be allocated the band 1.6 - 10MHz and the in-house band would be allocated the band 10 – 30MHz.

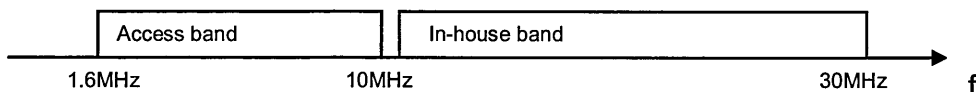


Figure 3-2 – ETSI TS 101 867 coexistence proposal

Furthermore each house is provided with a dedicated frequency block which is separate from those in the close vicinity to avoid signal collision in the in-house bands. It is analogous to the method used by radio stations who use a different frequency band on adjacent transmitters but use the same frequencies where no line of site signal path exists.

An alternative to separating access and in-house PLT in the frequency domain is to separate them in the time domain using TDM. In a TDM scheme, time is divided between access and in-home systems so that in any predefined interval, only one of the two systems is transmitting and occupying the entire available frequency band. Equally for houses that are physically collocated only one house can transmit and receive at any point in time. The separation of houses is undertaken by allocation of

each house to a cell and the timeslots for each cell are managed by programming the timeslots into the modems either statically or dynamically based on the number of modems transmitting. The TDM mechanism tends to be less efficient because each modem has to wait for its dedicated timeframe before transmitting and receiving its data. This mechanism however is used in military systems as a robust anti-jamming methodology and therefore in the PLT environment provides good rejection of unwanted interference in noisy environments.

In the PLT industry there is no common standard method for minimising collisions and in fact some manufacturers use a hybrid of FDM for access/in-house separation and TDM for house to house separation. Within each method (FDM/TDM) each manufacturer uses subtly different methods to achieve the modulation such as Orthogonal Frequency Division Multiplexing (OFDM) or Direct Sequence Spread Spectrum (DSSS). The obvious threat from this lack of standardisation is that whilst the service provider can control separation in the access band, users are free to procure their own in-house systems. Various researchers have proposed standard methodologies but at the time of writing there is no set direction or time period for standardisation.

3.2 ELECTROMAGNETIC RADIATION

As the main topic of this thesis is electromagnetic interference and arguments will be made against the assertions of other pieces of research, it is imperative that the underlying theory of electromagnetic radiation is understood. The basic electromagnetic laws are credited to mathematician and theoretical physicist James Clark Maxwell and are commonly known as Maxwell's equations. Individually they had been known before as Gauss's law for magnetism, Faraday's law of induction and Ampere's circuital law. Maxwell corrected Ampere's law and gave rise to the concept of a self-perpetuating electromagnetic wave. His treatise on electromagnetics (Maxwell

1873) was the first unified theory of electromagnetism and along with the Lorentz force law comprises the accepted classical electromagnetic theory. Each of Maxwell's equations are explained in detail below, built up by the underlying theory of each.

Firstly, it is worth noting that Maxwell's equations can be represented in differential or integral forms and also simplified for free space conditions. For the purposes of this thesis they will initially be discussed in integral form as that is the form that best suits the macroscopic nature of electromagnetic radiation with respect to PLT. Secondly, to understand the concept of electromagnetic radiation it is necessary to understand how an electromagnetic wave is generated and how it propagates. This necessitates a discussion of the magnetic and electric fields, how they are generated and how they interact independently of each other. Finally, most discussions on Maxwell's equations begin by explaining the Lorentz force as this is the physical force on charges and is the fundamental physical relationship between electric and magnetic components. This relationship will be explained in differential form as it relates to microscopic quantities.

3.2.1 Lorentz Force Law

During the 19th century the concept of the electric charge was demonstrated experimentally and it was shown that charges exerted a force on other charges at a distance (like charges repel and unlike charges attract). The force (F) can be described mathematically as

$$\vec{F}_E = q\vec{E}$$

where q is an idealized test charge and E is the electric field produced by all the other charges in the vicinity. The electric field can be described by a scalar potential field V , which is related to the electric field by

$$\vec{E} = -\vec{\nabla}V$$

where $\vec{\nabla} = \frac{\partial}{\partial x}\hat{x} + \frac{\partial}{\partial y}\hat{y} + \frac{\partial}{\partial z}\hat{z}$ is the vector operator “del” which when applied to a scalar returns a vector representing the spacial rate of change of the scalar quantity (i.e. gradient). It was also noted experimentally that a moving charge will experience a force which is a function of its velocity v when moved through a magnetic field B . The force is exerted perpendicular to the velocity and to the field

$$\vec{F}_B = q\vec{v} \times \vec{B}$$

Much like the electric field which is generated by surrounding charges, the magnetic field (B) is generated by all the other currents in the vicinity and any static magnetic dipole fields. Just as the electric field can be determined from a scalar field V , the magnetic field can be described in terms of a vector potential field A , which is related to the magnetic field by

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$\vec{\nabla} \times \vec{A}$ is the curl of \vec{A} which is a measure of the local rotation around a point. The vector potential is of limited observable value at the macroscopic level in relation to radiated fields but is mentioned as it has been mentioned in some early PLT papers.

If the electric and magnetic forces occur concurrently, then the force on the charge is given by the Lorentz force law

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (3-1)$$

3.2.2 Maxwell's Equations

The four Maxwell equations will be explained in detail in the remainder of the chapter.

In Integral form they are:

$$\oiint \vec{E} \cdot d\vec{S} = \iiint \frac{\rho}{\epsilon} dV \quad (3-2)$$

$$\oiint \vec{B} \cdot d\vec{S} = 0 \quad (3-3)$$

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \iint \vec{B} \cdot d\vec{S} \quad (3-4)$$

$$\oint \vec{B} \cdot d\vec{l} = \mu \iint \vec{J} \cdot d\vec{S} + \mu\epsilon \frac{d}{dt} \iint \vec{E} \cdot d\vec{S} \quad (3-5)$$

where ρ is the charge density (C/m³), \vec{J} is the current density (A/m²) and dl , dS , dV are the integration variables for a line, surface or volume respectively.

The first of Maxwell's equations (Equation 3-2) is known as Gauss's Law. It relates the flux of the electric field intensity to the total charge enclosed by a surrounding surface as in Figure 3-3².

² Courtesy of San Diego State University

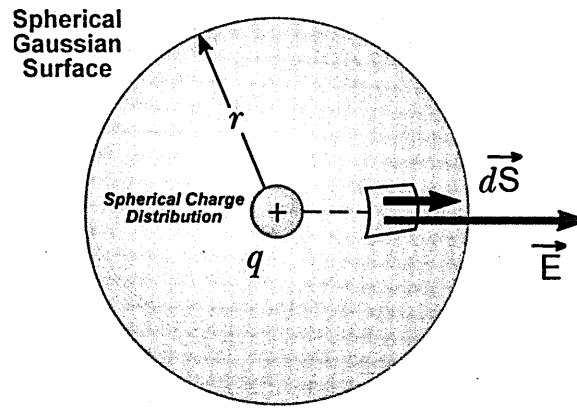


Figure 3-3 – Gauss's Law

The flux Φ_E is defined as

$$\Phi_E = \oint \vec{E} \cdot d\vec{S},$$

where $d\vec{S}$ is a vector outwardly normal to the surface and the integral is over the entire surface enclosing that region. Gauss's law therefore indicates that the total flux of electric field intensity through a closed surface (i.e. the change in the number of field lines passing through it) is proportional to the total charge contained within the volume enclosed by that surface. If there is no charge inside the surface, the net flux is zero.

The second equation (Equation 3-3) is also a form of Gauss's law, this time applied to the magnetic field but still in a closed surface. In the first equation the flux of an electric field originates and ends on charges. As can be seen from Maxwell's second equation the total magnetic flux through a surface is 0 and therefore there are no sources or sinks of magnetic flux. This leads to the concept that magnetic flux is continuous (or solenoidal) and that there are no magnetic monopoles. This is borne out by the fact that slicing a static magnet in half always leads to a magnet that has both north and south poles.

The third equation (Equation 3-4) is based on Faraday's law. Analogous to the electric flux, the magnetic flux is defined as

$$\Phi_B = \iint \vec{B} \cdot d\vec{S}$$

where the surface is now an open surface bounded by a conducting loop of length l .

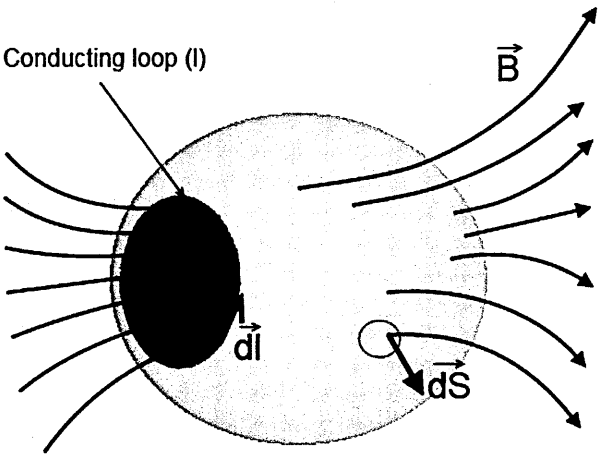


Figure 3-4 – Faradays Law

Faraday found that the induced electromotive force (EMF) that was generated around the loop (ideally there would be a gap in the loop to measure the EMF) was related to the rate at which the magnetic flux changed.

$$\text{emf} = -\frac{d\Phi_B}{dt}.$$

and

$$\text{emf} = \oint \vec{E} \cdot d\vec{l}.$$

Combining these two equations leads to Faraday's law, which demonstrates the experimental concept that a changing magnetic flux (either the surface area or the magnetic field changes with time) produces an electric field. This electrical field creates an EMF which acts in such a way as to resist the changes in the magnetic flux. In summary a time varying magnetic field creates an electric field and in a conductor causes a current to flow. Maxwell's final equation is known as Ampere's Law. In its original form as expressed by Ampere, it related the number of magnetic field lines surrounding a surface to the total current which was enclosed where \vec{J} is known as the current density.

$$\oint \vec{B} \cdot d\vec{l} = \mu \iint \vec{J} \cdot d\vec{S} \tag{3-6}$$

The summation across the surface of all $\vec{J} \cdot d\vec{S}$ is the enclosed current and the loop can be any arbitrary path that totally encloses the current. This is shown diagrammatically in Figure 3-5:

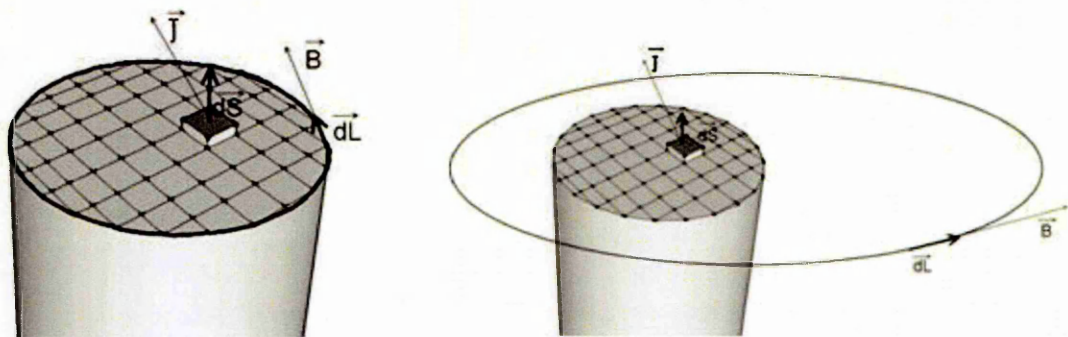


Figure 3-5 – Amperes Law (diagram)

Maxwell noted that the use of Ampere's law in the form of Equation 3-6 led to a violation of the conservation of energy for the electric and magnetic fields and hypothesised the existence of an additional current, the displacement current, which is defined as

$$i_d = \epsilon \iint \frac{\partial \vec{E}}{\partial t} \cdot d\vec{S}$$

When this is combined with Ampere's law in a region with no physical currents, one obtains

$$\oint \vec{B} \cdot d\vec{l} = \mu \epsilon \frac{d\Phi_E}{dt}.$$

In other words, just as a time varying magnetic flux causes a circulating electric field, a time varying electric flux causes a magnetic field which ultimately leads to the conclusion that electromagnetic fields can be self perpetuating and leads to the concept of the electromagnetic wave. The constant ϵ is the electric permittivity of the medium and in free space $\epsilon = \epsilon_0$ and is known as the permittivity of free space and has a value of $\epsilon_0 = 8.8542 \times 10^{-12} \frac{C^2}{N \cdot m^2}$. The constant μ is the magnetic permeability of the medium and in free space $\mu = \mu_0$ and is known as the permeability of free space and has a value of $4\pi \times 10^{-7} \text{ H/m}$.

3.2.3 Differential Form of Maxwell's Equations

In order to derive the wave nature of an electromagnetic field it is necessary to state Maxwell's equations in their differential form. The conversion from integral to differential form requires two important aspects of vector calculus, Gauss's divergence theorem and Stokes's theorem. Gauss's divergence theorem states that the net flux of a vector field (F) through a closed surface is equal to the integral of the divergence of that field over the volume contained in the surface.

$$\oint \vec{F} \cdot d\vec{S} = \iiint \vec{\nabla} \cdot \vec{F} dV \quad (3-7)$$

Similarly, Stokes's theorem implies that the flux through a closed loop is equal to the integral of the curl of the field over the area enclosed by the loop

$$\oint \vec{F} \cdot d\vec{l} = \iint \vec{\nabla} \times \vec{F} \cdot d\vec{S} \quad (3-8)$$

The differential operator $\text{del}(\nabla)$, which represents the spatial rate of change can be applied in shorthand notation to simplify the mathematical representation of the gradient of a scalar field and the divergence and curl of vector fields. A detailed explanation is provided by Kraus (Kraus 1991).

The divergence theorem when applied to Maxwell's first two equations provides

$$\iiint \frac{\rho}{\epsilon} dV = \oint \vec{E} \cdot d\vec{S} = \iiint \vec{\nabla} \cdot \vec{E} dV$$

and

$$0 = \oint \vec{B} \cdot d\vec{S} = \iiint \vec{\nabla} \cdot \vec{B} dV.$$

These relations are equal for any volume and therefore they become

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon}$$

and

$$\vec{\nabla} \cdot \vec{B} = 0$$

Applying Stokes's theorem to Maxwell's final two equations leads to

$$-\iint \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} = \oint \vec{E} \cdot d\vec{l} = \iint \vec{\nabla} \times \vec{E} \cdot d\vec{S}$$

and

$$\mu \iint \left(\vec{J} + \varepsilon \frac{\partial \vec{E}}{\partial t} \right) \cdot d\vec{S} = \oint \vec{B} \cdot d\vec{l} = \iint \vec{\nabla} \times \vec{B} \cdot d\vec{S}$$

These relations hold true for any surface bounded by a closed loop and therefore Maxwell's final two equations become

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

and

$$\vec{\nabla} \times \vec{B} = \mu \left(\vec{J} + \varepsilon \frac{\partial \vec{E}}{\partial t} \right)$$

The previous paragraphs have explained the individual nature of the electric and magnetic fields. The idea of the displacement current postulated by Maxwell gave rise

to the concept that changing electric fields generate magnetic fields, and changing magnetic fields generate electric fields and this can take place in the absence of charges and currents. Maxwell further postulated mathematically that electromagnetic fields were wave like. As it is the electromagnetic wave that gives rise to electromagnetic interference due to PLT this is explained further.

3.2.4 Electromagnetic Wave Equation

In a vacuum and in the absence of charges and currents, Maxwell's equations can be simplified to:

$$\vec{\nabla} \cdot \vec{E} = 0 \quad (3-9a)$$

$$\vec{\nabla} \cdot \vec{B} = 0 \quad (3-9b)$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3-9c)$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} \quad (3-9d)$$

If one takes the free space version Maxwell's third equation (3-9c) which represents a changing magnetic field and takes the curl of both sides one obtains:

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} = -\vec{\nabla} \times \frac{\partial \vec{B}}{\partial t} \quad (3-10)$$

Using vector identities the left hand side of Equation 3-10 can also be rewritten in terms of the electric field as:

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} = \vec{\nabla}(\vec{\nabla} \cdot \vec{E}) - (\vec{\nabla} \cdot \vec{\nabla})\vec{E} = -\nabla^2 \vec{E} \quad (3-11)$$

To evaluate the right hand side of Equation 3-10 one can use the Maxwell's final equation to obtain

$$-\vec{\nabla} \times \frac{\partial \vec{B}}{\partial t} = -\frac{\partial}{\partial t} (\vec{\nabla} \times \vec{B}) = -\frac{\partial}{\partial t} \left(\mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right) = -\mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

Combining with Equation 3-11 one obtains

$$\nabla^2 \vec{E} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} \quad (3-12)$$

which is recognizable as a standard three dimensional wave equation in this case for the electric field. From the standard wave equation one can derive the velocity of an electromagnetic wave in free space (given the symbol c) - a result that was demonstrated by experiment after Maxwell postulated it.

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \frac{1}{\sqrt{(4\pi \times 10^{-7} \frac{\text{m} \cdot \text{kg}}{\text{C}^2}) (8.85 \times 10^{-12} \frac{\text{C}^2}{\text{J} \cdot \text{m}})}} \approx 3.00 \times 10^8 \text{ ms}^{-1} \quad (3-13)$$

3.2.5 Energy in an Electromagnetic Wave

In common with other waves, the electromagnetic wave transports energy. The energy density (energy per unit volume - U_E) stored in an electric field can be written as

$$u_E = \frac{1}{2} \epsilon_0 E^2.$$

Similarly, the energy density stored in the magnetic field is

$$u_B = \frac{1}{2\mu_0} B^2.$$

Since $c = 1/\sqrt{\mu_0\epsilon_0}$, then

$$u_E = \frac{1}{2}\epsilon_0 E^2 = \frac{1}{2}\epsilon_0 c^2 B^2 = \frac{1}{2}\frac{\epsilon_0}{\mu_0\epsilon_0} B^2 = \frac{1}{2\mu_0} B^2 = u_B$$

Thus, the total energy density is shared between the constituent electric and magnetic fields

$$u = u_E + u_B$$

The flow of electromagnetic energy, S represents the energy per unit area. For any arbitrary small interval of time Δt , only the energy contained in the volume $V = cA\Delta t$ will cross the area A . Thus,

$$\begin{aligned} S &= \frac{U}{A\Delta t} = \frac{uV}{A\Delta t} = \frac{ucA\Delta t}{A\Delta t} = uc = (u_E + u_B)c = \left(\frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{1}{\mu_0} B^2 \right) c \\ &= \frac{1}{2\mu_0} (\epsilon_0\mu_0 E^2 + B^2) c = \frac{1}{2\mu_0} \left(\frac{cEB}{c^2} + \frac{EB}{c} \right) c = \frac{1}{\mu_0} EB \end{aligned}$$

In free space (or any isotropic media), the energy flows in the direction of propagation of the wave. The corresponding vector \vec{S} is known as the Poynting vector

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} \quad (3-14)$$

If \vec{E} and \vec{B} are both harmonic waves, then $\vec{E} \times \vec{B}$ also cycles harmonically. As \vec{E} and \vec{B} are rapidly varying their instantaneous values are difficult to measure and therefore it is useful to average \vec{S} over a cycle. The time averaged value of the magnitude of the Poynting vector is the average power density in Wm^{-2} of an electromagnetic wave. A useful visualisation is at optical frequencies where it is commonly known as irradiance i.e. the light per unit area.

3.2.6 An Alternative View

Most treatments of Electromagnetics follow the arguments above which mathematically describe any electromagnetic wave in any medium, and in the cases above, free space. It is not always easy to understand what physical interactions (albeit abstract) are taking place and how they occur, and hence it is worth briefly discussing those physical interactions. As mentioned when discussing the Lorentz Force, charges that are separated have an attraction or repulsion to each other depending upon whether they are positive or negatively charged (like charges repel and unlike attract). It follows that if a charge is made to move, the force it exerts on surrounding charges is through a transfer of momentum and energy. This ability to undertake action at a distance gives rise to the mathematical concept of a field that describes the ability of a charged particle to exchange energy with others. The field cannot exist without the charged particle and therefore when discussing fields it is important to remember that fields and charged particles exist and there is no distinction between the two.

If a charge is placed in the vicinity of a field it will tend to move and therefore because current is a flow of charge applying a field to charges causes a current to flow. A conductor is defined as a medium that has charges that are free to move. If a field is applied, the charges will flow throughout the conductor with the prevailing field and each charge contributes to that field. Eventually a natural equilibrium takes place when the applied field and the field due to the charges within the conductor cancel out. This

is analogous to pouring water into a bath whereby the gravity “field” causes the water particles to come to rest at the natural water level in the bath. If the applied field to the conductor changes, the charges will readjust their positions until the potential is uniform within the conductor. The analogy with water would be to tilt the bath until the natural water level is maintained. This redistribution of charged particles by an applied field is known as “induction” or more formally induction of a current in a conductor by a field. The cases described so far have assumed a uniform field is applied and therefore the charges distribute themselves from one predetermined level to another. However in communications systems the field is made to change continually (often sinusoidally) by continually changing the applied field. This is analogous to dipping a finger into the bath of water above at a repetitive time period and observing the water redistributing itself towards equilibrium by the observation of waves out from the source. The final clarification, therefore, is to determine what is happening that causes the field to apparently leave the conductor and radiate through space causing the radiated emission from PLT.

It is important to note that the rules for fields and how they are modelled by Maxwell's Equations are true in all of space whether that is in free space, in a conductor or in a dielectric. It is however due to the properties of a conductor that they can be treated as boundaries to the field rather than materials embedded in the field. When a field is applied to a conductor, because the free charges seek to maintain equilibrium, the field that they create causes a further re-radiation. The amount of energy that is radiated is a function of the structure of the conductor and the frequency of operation. At low frequencies (50Hz) conductors tend to radiate the energy predominantly in the direction of the conductor and hence Maxwell's equations can be simplified to basic circuit theory. At higher frequencies however the fraction of energy that radiates out of the conductor increases and this is the main cause for PLT radiating when higher frequencies are applied. Another analogy is the transmission of HF around the cavity

created between earth and the ionosphere. At HF frequencies the field radiates as far as the ionosphere then appears to be reflected back (Figure 3-6).

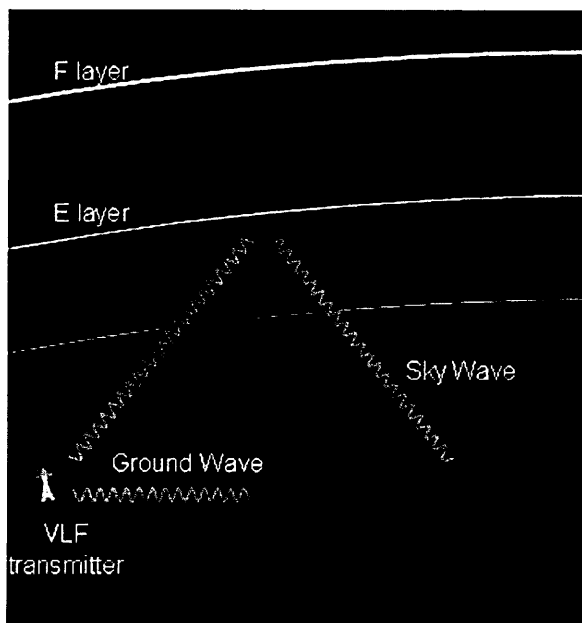


Figure 3-6 – Re-radiation from the ionosphere (sky wave)

In reality the field causes the ionosphere to vibrate and radiate energy back into the cavity. At higher frequencies (i.e. microwave) the radiated field tends to pass through the ionosphere hence the use of microwave frequencies for space communications. Some PLT papers describe this mechanism (sky wave) as a potential long range effect on victim receivers.

3.2.7 Infinitesimal dipoles

Many of the early PLT papers that attempted to predict how interference from PLT would propagate through free space relied upon Maxwell's equations. Whilst Maxwell's equations predict the values of electric and magnetic field strength at any point in space and time, they are not easy to apply to a physical setup as they involve complex integrals that are difficult to solve. In most physics text books the concepts associated with Maxwell's equations are first described using the most simplistic form of electromagnetic source - the infinitesimal dipole. An infinitesimal dipole is used

because it generates an electric field and because its own physical size is very much smaller than the distance to the point in space where the measurement takes place. Its own size can be ignored and therefore this is useful as it simplifies the integral that has to be solved. Figure 3-7 below demonstrates this graphically.

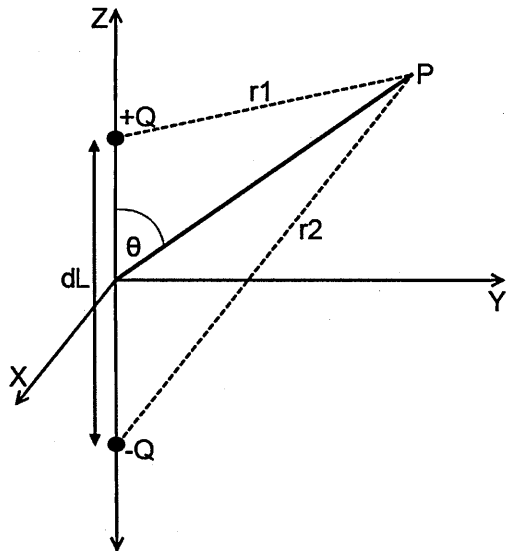


Figure 3-7 – Radiation from infinitesimal dipole

An infinitesimal dipole can be visualised as two charges (Q) which are not free to move separated by an infinitesimally small distance, dL . The electrostatic potential at the point P can be obtained from summing the potentials from each of the charges using Coulombs Law. As dL is infinitesimally small compared with the distance to the point P then the distances r_1 and r_2 are effectively parallel. This simplification when applied to Coulomb's Law leads to the electrostatic potential, V at a point from a dipole as

$$V = \frac{QdL\cos\theta}{4\pi\epsilon_0r^2} \tag{3-15}$$

The electric field can be derived by taking the gradient of the electrostatic potential. If the environment being modelled has a long straight wire of length L as a source, then it can be modelled as a sum of all infinitesimally dipoles (dL) which make up the length of wire. Summing the contribution of all infinitesimally small dipoles gives the electric field at the point P .

3.2.8 Limitations

The purpose of describing paragraphs 3.2.1 - 3.2.7 in such detail is to demonstrate the complexity in using Maxwell's equations to predict electromagnetic radiation at the macroscopic level. The solutions involve surface and volume integrals of vector quantities which can only be easily solved when they can be simplified to regularly shaped objects. The three common examples are an infinitely long thin wire, a cylinder and a sphere (or in the limiting case a point source). In many problems these simplifications can be used by making assumptions such as the measurement distance from a wire is very close and therefore it looks infinitely long or the measurement distance from an object is so far it looks like a small point source. For the PLT problem however this is rarely the case due to the very irregular nature of mains wiring (i.e. wires run horizontally and vertically and the live, neutral and earth form loops in the UK). Most of the early research on radiation from PLT made theoretical predictions but did not list the assumptions above or caveat the results accordingly. This method of predicted radiation should therefore only be used as a very rough indicator of potential field strength and caveated accordingly.

These limitations apply equally to computer modelling where more complex antenna structures can be modelled and solved using computational techniques. In the case of PLT even an oversimplified single ring main consisting of two loops (live and neutral) whose diameter could be 8m but placed 5mm apart and separated with a ground plane (the earth wire) would require very significant computing power. When appliances are added of frequency dependent impedance the computational problem becomes unmanageable. The use of computer models to predict the radiated emissions of PLT must therefore equally be caveated and adjusted for errors.

As will be seen later, a key assumption of all radiated emissions for EMC compliance purposes is that the radiated wave is a plane wave and that the electric component and magnetic component are perpendicular to each other. This leads to a transverse electromagnetic wave whose direction of travel (and the Poynting Vector) is also perpendicular to both electric and magnetic components as shown in Figure 3-8.

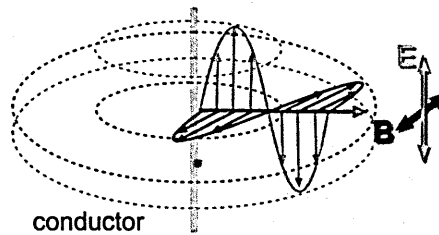


Figure 3-8³ – Transverse electromagnetic wave

The concept of the transverse wave is fundamentally important because to allow comparative and repeatable measurements to be undertaken the wave must be predictable. The question then is “when is an electromagnetic wave a plane wave?” There are a range of factors, namely: errors, frequency, source dimensions and source structure which determine how far from the source a wave can be considered a plane wave. To understand this fully the exact nature of an electromagnetic wave and its relationship to its source must be understood. The following paragraphs are critical to understanding the near-field and the far-field of an electromagnetic wave and at what point the electromagnetic wave can be considered plane.

3.2.9 Near-field/far-field

When antennas radiate the structure of the wave can be described in terms of its electric and magnetic components and also by the part of the field that radiates and the part of the field that does not. MacLeish, 1992 explains that when a charge or collection of charges is oscillated it causes a change to the associated field which propagates through space as a wave. The components of the wave are based on the static and

³ Courtesy of Canadian Space Agency

dynamic fields and Strauss, 2001 further explains that the structure of the wave is dependent on whether the source is predominantly magnetic or electric in nature. For a charge dipole (Figure 3-7), the field is predominantly electric and consists of components that are based on the static Coulomb field that attenuate as $1/r^3$ and a radiating electric field that has components in $1/r^2$ and $1/r$. Equally for a small current loop which is predominantly magnetic in nature there is a magnetostatic component that attenuates as $1/r^3$ and a radiating magnetic field that has components in $1/r^2$ and $1/r$. From Maxwell's equations it is understood that when either a magnetic or electric field is made to change there is a corresponding electric or magnetic field respectively. Figure 3-7 has been redrawn as a short (in comparison with wavelength) sinusoidal time-varying current element dipole of length dL below.

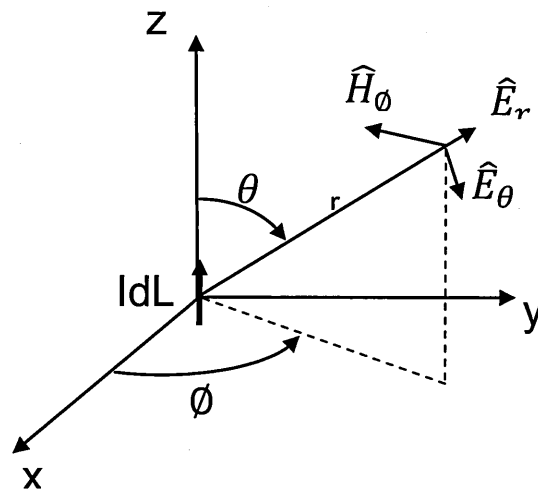


Figure 3-9 – Sinusoidal infinitesimal dipole showing E and H components

If the time varying charge at each end of the dipole is:

$$Q(t) = Q_0 \sin(\omega t)$$

and since current is rate of change of charge then

$$I(t) = \frac{\partial Q(t)}{\partial t} = \omega Q_0 \cos(\omega t)$$

Shelkunoff, 1943 derived from Maxwell's equations the individual components of the generated electromagnetic wave as:

$$E_{\theta} = j30 \beta^2 Idz \left(\frac{1}{(\beta r)} - \frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3} \right) \sin \theta e^{-j\beta r}$$

$$E_r = 60 \beta^2 Idz \left(\frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3} \right) \cos \theta e^{-j\beta r}$$

$$H_{\phi} = j \frac{\beta^2}{4\pi} Idz \left(\frac{1}{(\beta r)} - \frac{j}{(\beta r)^2} \right) \sin \theta e^{-j\beta r}$$

$$E_{\phi} = H_r = H_{\theta} = 0$$

The points of note from the above equations are that both electric and magnetic fields are present and contain components of $\frac{1}{(\beta r)}, \frac{j}{(\beta r)^2}, \frac{1}{(\beta r)^3}$ where $\beta = \lambda/2\pi$ and $\lambda = c/f$, where c is the velocity of an electromagnetic wave and f is its frequency. In the near-field the electric field components dominate but degrade rapidly with distance due to the $1/r^3$ term.

One can define the transition of the near-field to the far-field by using

$$\beta r = \frac{r}{\lambda/2\pi} \quad \text{when } r_0 = \lambda/2\pi \quad \text{and} \quad \beta r = 1. \quad \text{This is the near to far transition and the}$$

terms are of the same order of magnitude.

When $r \ll r_0$ the field is predominantly electric and this is the near field

When $r \gg r_0$ the field contains both components and the relationship between E and H is the characteristic impedance of the medium. In free space this is 120π or 377Ω .

One might ask the question “is there a magnetic equivalent”? Whilst short dipoles create electric fields, current loops create magnetic fields. A small circular loop oriented in the x – y plane (horizontal) produces the following field components:

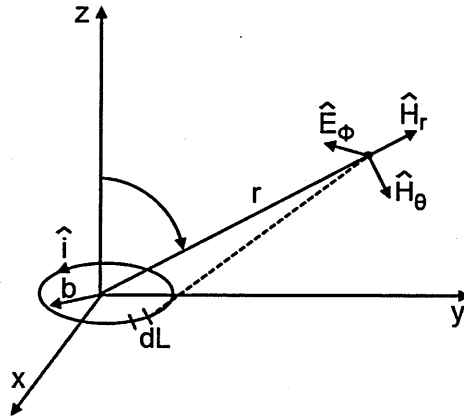


Figure 3-10 – Sinusoidal infinitesimal loop showing E and H components⁴

$$E_{\phi} = 30 \beta^2 dL \left(\frac{1}{(\beta r)} - \frac{j}{(\beta r)^2} \right) \sin \theta e^{-j\beta r}$$

$$H_r = \frac{\beta^3}{2\pi} dL \left(\frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3} \right) \cos \theta e^{-j\beta r}$$

$$H_{\phi} = -\frac{\beta^3}{4\pi} dL \left(\frac{1}{(\beta r)} - \frac{j}{(\beta r)^2} - \frac{1}{(\beta r)^3} \right) \sin \theta e^{-j\beta r}$$

$$E_r = E_{\theta} = H_{\phi} = 0$$

In the far-field both electric and magnetic sources look the same. That is to say that to measure the fields in the far-field using either a loop antenna or monopole antenna will result in the same measured value and there is no way of knowing whether the source is predominantly electric or magnetic. In the near-field however the fields are predominantly electric or magnetic depending on their source, and impedance is

⁴ Courtesy of Conformity Magazine

therefore not the free space impedance of 377Ω . Figure 3-11⁵ demonstrates the relative impedance of both electric and magnetic fields at distances relative to the wavelength - assuming that the sources are infinitesimally small.

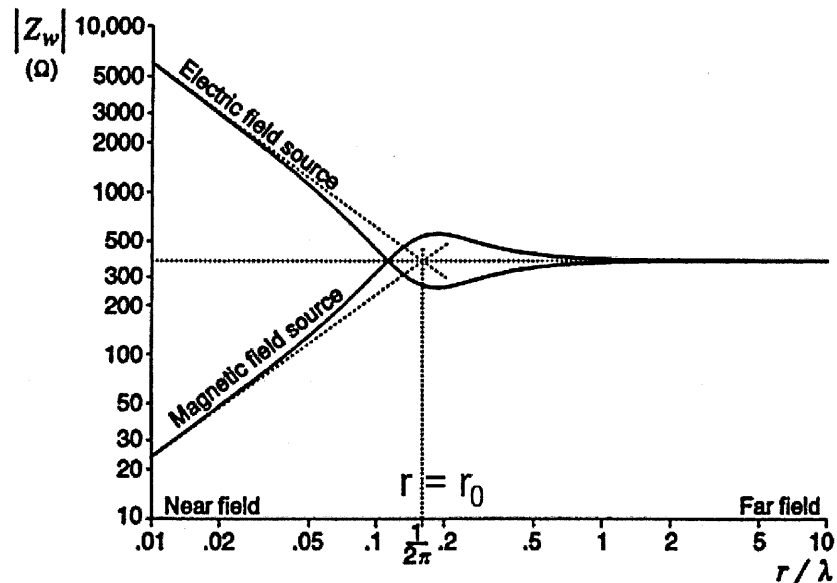


Figure 3-11 – Electric and magnetic field strengths of infinitesimal sources

3.2.10 Far-field/near-field boundary

From the explanation above it appears that from Maxwell's equations the distance to the far-field is well defined, that is at distances where $r_0 \gg \frac{\lambda}{2\pi}$. This explanation however is only valid when the source is infinitesimally small. Similar to the arguments of paragraph 3.2.8 above, Maxwell's equations are useful when the integrals can be simplified through geometry. The concept of an infinitesimal dipole or loop is useful in radio communications engineering where the source and receiver are some kilometres apart. Using an example at the lower end of the PLT spectrum of 3MHz, the wavelength is 100m. The far-field when using $\frac{\lambda}{2\pi}$ is around 16m. For the case when $r_0 \gg \frac{\lambda}{2\pi}$ then using a conventional engineering assumption that "much greater than"

⁵ Courtesy of Conformity Magazine

approaches 10^2 then the far field can be assumed to be beyond 1km. This is a fair assessment in radio communications where most users are some distance from the source, but not so at EMC radiated emission measurement distances of 1m, 3m, 10m or even 30m for some FCC measurements.

Capps, 2001 discusses various common “assumed” far-field distances and terminology, some of which is borrowed from optics. The first confusion arises from the use of terminology of far-field and near-field. The far-field concept is useful because it defines when an electromagnetic wave becomes a plane wave. But the definition of “plane” is based on how much error can be tolerated in a measurement. For example antenna text books are interested in waves that arrive at an antenna and the maximum phase difference presented across the antenna is $\lambda/8$. In optics text books, the Rayleigh criterion is often discussed which is similar to the antenna error but uses a phase error due to differences in path length of $\lambda/16$. The key point is that before a definition of a plane wave and hence the far-field can be defined the tolerable error must be stated.

The second point of note is to understand the application of the plane wave. EMC engineers who design shields rely on a large ratio of wave impedance to shield impedance and therefore are concerned about the impedance of the wave. As the impedance is well defined in the far field (377Ω), shields can be designed. If, however, a shield is designed for a wave that is predominantly electric it will be ineffective against a low impedance magnetic wave. For this reason shield engineers tend to define the far-field as $5\lambda/2\pi$. Antenna engineers on the other hand are interested in the launch and receive conditions of waves and the associated phase error. The following

figures⁶ shows universally accepted boundaries derived from various text books on EMC shielding and Antenna theory and further shows the variation in their application:

Definition for shielding	Remarks	Reference
$\lambda/2\pi$	1/r terms dominant	Ott, White
$5\lambda/2\pi$	Wave impedance=377 Ω	Kaiser
For antennas		
$\lambda/2\pi$	1/r terms dominant	Krause
3λ	D not $\gg \lambda$	Fricitti, White, Mil-STD-449C
$\lambda/16$	Measurement error<0.1 dB	Krause, White
$\lambda/8$	Measurement error<0.3 dB	Krause, White
$\lambda/4$	Measurement error<1 dB	Krause, White
$\lambda/2\pi$	Satisfies the Rayleigh criteria	Berkowitz
$\lambda/2\pi$	For antennas with $D \ll \lambda$ and printed-wiring-board traces	White, Mardiguian
$2D^2/\lambda$	For antennas with $D \gg \lambda$	White, Mardiguian
$2D^2/\lambda$	If transmitting antenna has less than 0.4D of the receiving antenna	MIL-STD 462
$(d+D)^2/\lambda$	If $d > 0.4D$	MIL-STD 462
$4D^2/\lambda$	For high-accuracy antennas	Kaiser
$50D^2/\lambda$	For high-accuracy antennas	Kaiser
$3\lambda/16$	For dipoles	White
$(D^2+d^2)/\lambda$	If transmitting antenna is 10 times more powerful than receiving antenna, D	MIL-STD-449D

Figure 3-12 – Definitions of near-field/far-field boundary

It is therefore fair to say that the concept of the far-field is well understood but its application can cause confusion. This is further exacerbated by terminology. As well as there being a near-field/far-field model there is also a three region model with an intermediate field or transition zone. Depending on whether the application is optics, communication theory, EMC theory or general electrodynamics defines the exact terminology but common terms are “Fresnel Region” and “Fraunhofer Region”, “Reactive field” and “Radiation Region”. Figure 3-13⁷, which is shown only for comparative purposes, identifies some common terms and shows their components in the near and far fields:

⁶ Courtesy of Charles Capps senior EMC engineer Delphi Automotive

⁷ Courtesy of Charles Capps senior EMC engineer Delphi Automotive

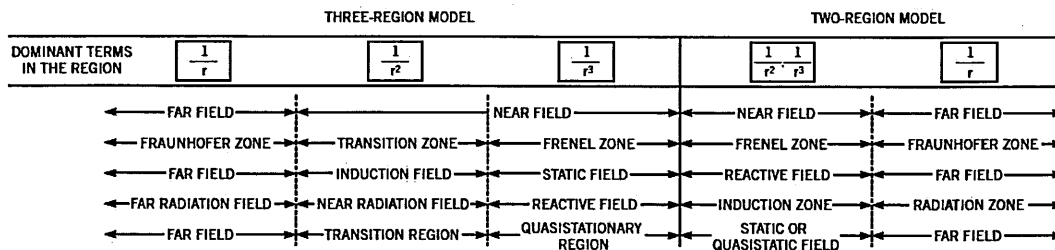


Figure 3-13 – Two and three region models

Recognising that with PLT, EMC measurements are not conducted at distances significantly greater than the far-field transition distance; many researchers have adopted the antenna far-field formula (known in optics as the Rayleigh Distance).

$$r \geq \frac{2D^2}{\lambda} \quad (3-16)$$

where D is the largest linear dimension of the antenna and λ is the wavelength. Trzaska, 2001 argues that this formula has utility in communications theory because it allows for calculation of the beginning of the far-field (in his examples a large LF transmitter and a small dish). It is however still dependent on source structure and directivity. He further argues that the results are not always easy to interpret and *“in the case of more complex structures an interpretation of the boundary will be incomparably more difficult”*. Furthermore because the near-field to far-field transition is not discontinuous, he derives an alternative equation for the near-field boundary, namely:

$$r \leq \frac{D}{4} + \frac{D}{2} \left(\frac{D}{\lambda} \right)^{\frac{1}{3}} \quad (3-17)$$

A number of formulae that are used commonly in science and engineering have been presented in paragraph 3.2.10 can be seen to be quite different. In summary, it is imperative that one understands the basis of the derivation of formulae and the

limitations imposed, particularly when referring to PLT measurements because the source structure is not comparable to a loop or a dipole. The key point to take from this lengthy discussion is that the near-field/far-field boundary is only clearly understood when the source and the measurement conditions are well defined. The equations stated in Figure 3-12 above are all based on simplifications of Maxwell's Equations and are only accurate under certain conditions. They apply specifically to the following sections on field attenuation and also to the use of loop antennas when measuring electric fields. Almost all PLT EMC papers make use of the formulae but make no statements of their validity or associated error, and instead quote measurement results in dB μ V/m to 1 decimal place.

3.2.11 Attenuation with distance

In order for an estimate to be made of the effect of a source radiator on a victim receiver, one must measure the emitted radiation at the point in space where the victim would be placed. This is often not possible because in reality the victim may be mobile or measurement limitations may not permit a measurement antenna to be placed there. In the case of EMC measurement, the background noise may be larger than (or a significant contributor to) the signal being measured. In these circumstances it is normal to extrapolate the known field at a measured location to one somewhere else. As mentioned in section 2, this is the key method used by many researchers that aim to estimate whether PLT will affect a victim receiver. In the case of free space radiation in the far-field of the source, the attenuation with distance is assumed to be $1/r$ for both the electric and magnetic fields and $1/r^2$ for the power (based on the Poynting Vector formula). It is not strictly accurate to apply this close to the Earth's surface because the effects of a ground plane can cause reflections that will increase or reduce the measured field depending on frequency, ground conductivity, directivity and emitted amplitude. The effects in practice appear to be marginal and on average most sites

even without a calibrated ground plane would tend to have $1/r$ or 20dB of attenuation per decade of distance $\pm 6\text{dB}$ (Montrose and Nakauchi 2006).

As one moves back toward the source and into the near-field, there are terms in $1/r^2$ and $1/r^3$ that would contribute towards attenuation with distance which is different to $1/r$. These would equate to an attenuation of 40dB and 60dB (Kee 2011) per decade of distance respectively. In real-world EMC measurement in a National Measurement Accreditation Service (NAMAS) approved test house all measurements would be taken in the far-field on a calibrated site. If the specific test required a near-field measurement, either the measurement antenna would be calibrated differently or representative measurements from a known source would be taken at set distances to obtain a more accurate attenuation with distance. The uncertainty associated with attenuation with distance is also significant if one wishes to compare measurements at different distances. Later on a comparison of EMC standards will show a graph that has been quoted in many PLT papers that attempts to show how different limits and test methods could be used to measure PLT. As they do not all measure at a common distance, a $1/r$ extrapolation has been used to allow comparison of each measurement limit. As has been shown, unless one is in the far-field, an attenuation of $1/r$ is not accurate and at least recognition of this and an estimate of the error should be quoted.

Another area of importance when discussing the near-field and far-field in EMC measurements is when applied to the use of specific antenna types. Figure 3-11 showed the field impedance of infinitesimal sources depending on whether they are predominantly electric or magnetic in nature. In the case of PLT, if one assumes that mains wiring is predominantly based on ring main architecture and ring main areas are similar to the floor space, then as a source of electromagnetic radiation, it is more likely to be similar to a loop than a dipole. As most measurements are taken in the near-field where the field is more likely to be magnetic than electric, most researchers agree that

the measurement should be taken with a shielded loop. When a magnetic field is presented to a loop antenna it generates an associated current in the loop. For the output to be useful as the input to a measuring device such as a spectrum or EMC analyser its output has to be converted to a voltage. The relationship between the applied magnetic field and the associated voltage presented to a measuring device is known as the antenna factor. It should be noted that there is also an antenna factor that associates the applied electric field to the presented voltage. As the remainder of this section is pertinent to loop antennas it should be assumed that it is the magnetic antenna factor that is being used. The equation for the magnetic antenna factor is:

$$AF^{\text{magnetic}} = \frac{H_{\text{incident}}}{V_{\text{received}}} \left(\frac{S}{m} \right) \quad (3-18)$$

As a quantity it is frequency dependant and is based on the effective aperture of the antenna, i.e. it has a resonant frequency based on its size and is less efficient at other frequencies. The antenna factor is based on measurements and when calculated is assumed to be in the far-field. Some manufacturers offer antenna factors at various distances that are common in EMC standards such as 3m and 10m. The point to note is that the antenna factor must be used at the distance at which it was calibrated. If the measurement distance is being brought back into the near-field then it cannot necessarily be adjusted by figures determined by a 1/r (20dB per decade).

3.2.12 Conversion limitations of H to E using free space impedance

The final consideration of far-field theory is when using a loop antenna to make a radiated measurement. Standard EMC radiated measurements below 30MHz tend to be of a magnetic nature and measured with a loop which results in limits stated in amperes per meter (A/m) or more usually dBμA/m. Measurements above 30MHz tend to be more accurate when measured with a monopole or dipole antenna representing the electric field. Within the PLT radiated emission debate it is often convenient to

relate the measured magnetic field to an equivalent electric field for comparison to higher frequency measurements and for correlation to the equivalent conducted measurement. The difficulty arises however because E is related to H through the wave impedance $Z = \frac{|E|}{|H|}$ and for a wave in free space is related to both the magnetic permeability of free space (μ_o) and the electric permittivity of free space (ϵ_o) such that

$$Z_o = \sqrt{\frac{\mu_o}{\epsilon_o}} \text{ where } \mu_o = 4\pi \times 10^{-7} \text{ H/m and } \epsilon_o = 8.854 \times 10^{-12} \text{ F/m}$$

Therefore

$$Z_o \approx 120\pi \approx 377\Omega \quad (3-19)$$

The free space characteristics are only applicable when the field is purely in the radiating zone which is in the far field. In this region one can measure either the electric or magnetic field and calculate the other irrespective of whether the source is loop-like or dipolar in nature. As one approaches the near-field the impedance of the source has contributory effects such that this is no longer the case. As an example, for an electric field source the $1/r^3$ component is electric and the $1/r^2$ component is magnetic. The impedance, which is the ratio of E to H, is therefore not constant and as one moves closer to the source the electric component dominates resulting in the impedance being much greater than 377Ω . Conversely for magnetic sources the $1/r^3$ component is magnetic and the $1/r^2$ component is electric leading to a lower value of impedance.

In EMC measurements, the measured value below 30MHz is in A/m and the limit value for comparison is in V/m and therefore a conversion is required. In the far-field one can assume the ratio of E to H to be 377Ω to make the conversion. In reality because most radiating measurements are in dB μ V/m or dB μ A/m the dB equivalent of 377 is added or subtracted at the same time as the antenna factor and any cable losses are

accounted for. The dB equivalent of multiplying or dividing 377Ω is to add or subtract 51.5dB which is derived from $20 \log(377)$. For a lower frequency PLT measurement, for example 1.6MHz, the measuring antenna will definitely be in the near-field irrespective of which formula is chosen resulting in an overestimation of the electric field strength because the loop-like source is primarily magnetic in nature. To clarify then, the measurement procedure is accurate but it is the reporting of the measured value as an electric field that causes the error. For this reason UK and US military standards that aim to protect communication equipment in the HF and VHF bands often measure near-field components independently. The electric field strength is measured with a 1m monopole which is sensitive to electric fields but not magnetic fields and its measured value compared to an electric field limit in V/m. The magnetic field strength is measured with a loop antenna and compared to a magnetic limit in A/m.

The following short abstract is taken from CISPR 16-1 (CISPR 2006) which is guidance for EMC measurements unless specified differently in a specific CISPR standard:

For measurement of the magnetic component of the radiation, either an electrically-screened loop antenna of dimension such that the antenna can be completely enclosed by a square having sides of 60 cm in length, or an appropriate ferrite-rod antenna, may be used. The unit of the magnetic field strength is A/m or, in logarithmic units, $20 \log(A/m) = dB(A/m)$. The associated emission limit shall be expressed in the same units. NOTE Direct measurements can be made of the strength of the magnetic component, in dB(A/m) or A/m of a radiated field under all conditions, that is, both in the near field and in the far field. However, many field strength measuring receivers are calibrated in terms of the equivalent plane wave electric field strength in dB(V/m), i.e. assuming that the ratio of the E and H components is 120π or 377Ω . This assumption is justified under far-field conditions at distances from the source exceeding one sixth

of a wavelength ($\lambda/2\pi$), and in such cases the correct value for the H component can be obtained by dividing the E value indicated on the receiver by 377, or by subtracting 51.5 dB from the E level in dB(V/m) to give the H level in dB(A/m). It should be clearly understood that the above fixed E and H ratio applies only under far-field conditions.

To obtain the reading of H (A/m), the reading E (V/m) is divided by 377 Ω : $H \text{ (A/m)} = E \text{ (V/m)} / 377\Omega$. To obtain the reading of H dB(A/m), 51.5 dB is subtracted from the reading E dB(V/m): $H \text{ dB(A/m)} = E \text{ dB(V/m)} - 51.5 \text{ dB}$.

The impedance $Z = 377\Omega$, with $20 \log Z = 51.5 \text{ dB}$, used in the above conversions is a constant originating from the calibration of field strength measuring equipment indicating the magnetic field in V/m (or dB(V/m)).

CISPR16 is the definitive EMC standard relating to methodology and the purpose of quoting the previous section directly is because it is fundamental to the understanding of magnetic field measurement and then applying it to an electric field intensity limit. It is therefore particularly surprising that so few technical papers on PLT make reference to it.

3.2.13 Common mode/differential mode

To complete the discussion of radiated emissions it is necessary to discuss common and differential mode currents and how these lead to radiation. These effects are aspects of the Lorentz Law and Maxwell's Equations at the macroscopic level but are sometimes misleadingly presented as phenomena in their own right. In reality they simply relate currents to the generation of electromagnetic fields primarily in collocated wires (i.e. parallel wires such as mains cables and twisted pairs etc).

Figure 3-14 shows two wires separated by a distance S and the associated field component E.

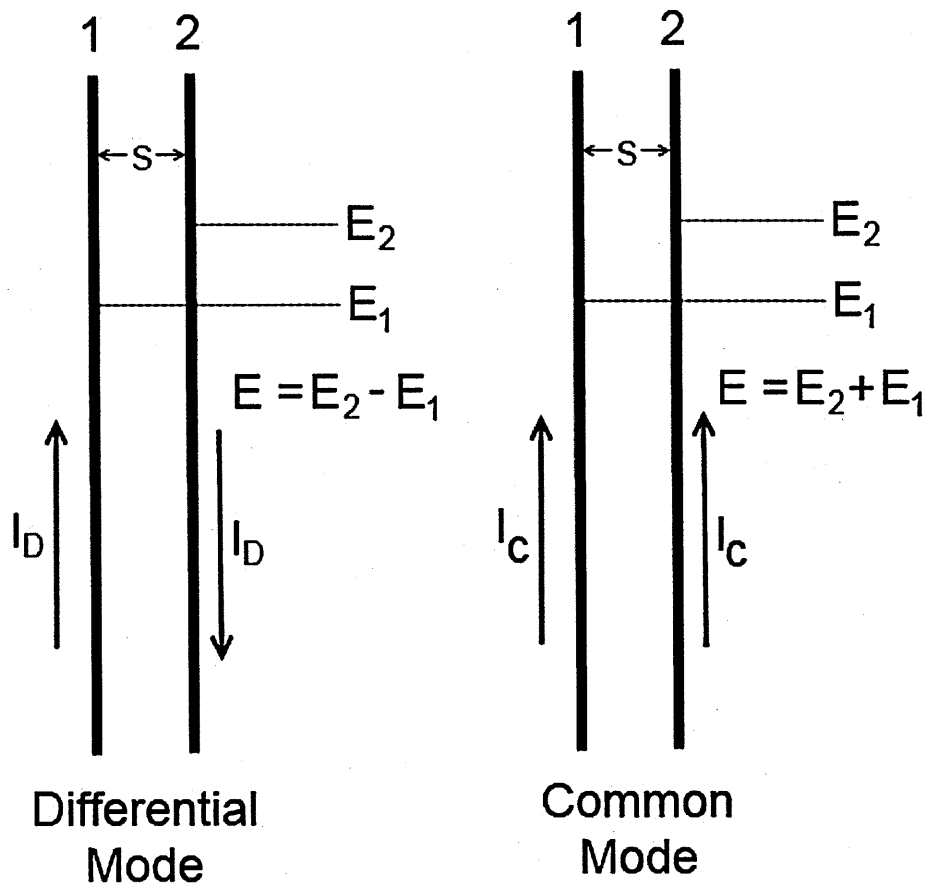


Figure 3-14 – Differential and common mode currents

In the first instance the currents are flowing in opposite directions (differentially) as would be the case in normal circuit theory. If one assumes that wire 2 is the return path of currents flowing in wire 1, then their magnitudes would be equal. In the second instance, there is seen to flow a current on both wires of the same magnitude that is not predicted by circuit theory – a common mode current. This is a result of an unbalance in the load leading to an impedance mismatch and hence partial reflection in the transmission system. In general the currents on a transmission system (such as mains wiring in PLT) consist of both differential and common mode currents. Because the wires are collocated, the radiated field due to a differential mode system leads to a cancellation of the fields between the wires thus the overall radiation from the system is reduced. In the case of the common mode system, because the currents are flowing in

the same direction the total radiation from the system is the sum of both radiated fields which leads to a much larger measured electromagnetic field. This mathematical difference in radiation leads certain authors to imply that there are two different methods at work but both types of current are in fact circuital demonstrations of Maxwell's equations. When designing equipment to be EMC compliant, it is therefore beneficial to understand the causes of common mode currents and attempt to reduce them resulting in an overall reduction of radiated emissions. Methods of achieving this are through the use of twisted pair and coaxial cables. The cables themselves do not change the cause of the common mode currents but provide a greater cancellation of the radiation between wires and consequently a reduction in the radiated emission. To reduce the emitted radiation from a power lead on an appliance, one would use a choke (coil of wire around a ferrite core) around the outside of the wire pair. Chokes present a high impedance to common mode currents and a low impedance to differential mode currents; the result being that the common mode currents get attenuated. The amount of attenuation or common mode rejection depends on the relative magnitude of choke impedance and load impedance at the frequencies of interest. In PLT terms this is not feasible because of the distributed nature of mains wiring much of which is hidden behind building walls.

3.3 EMC

The previous paragraphs have concentrated on the physics behind electromagnetic radiation to provide a better understanding of the rationale behind the following discussion on EMC testing and the associated standards. As will be discussed, the standard EMC measurements for the purpose of compliance measurement are normally undertaken in a controlled environment with a defined set of standards. For PLT however the compliance of a PLT modem is only part of the issue. Firstly it intentionally conducts along the powerline (which is normally strictly controlled by EMC standards) and secondly the PLT modem is only part of the system and testing it as a

standalone unit is only testing part of the final installation. The following paragraphs explain how EMC compliance is normally undertaken, compare different standards and explain the difficulties associated with EMC measurement of PLT.

3.3.1 EU Directive 2004/108/EC

International regulation of EMC is broadly undertaken in a similar way, and for products that are to be sold in the EU the importer/manufacture has obligations with respect to the EU directive which sets out the guidelines for which all member states should regulate EMC compliance. Within the EU, apparatus that complies with safety and environmental regulations is given the CE mark. The term "apparatus" is defined as any product supplied to an end-user. The only exclusions to EMC compliance is for apparatus that is EMC benign or "apparatus intended for incorporation into a given fixed installation and not otherwise commercially available". The Directive requires apparatus to be compliant as follows before the CE mark can be applied. It must:

- Comply with the "Protection Requirements"
- Undergo a "conformity assessment" procedure
- Have technical documentation available for inspection
- Be supplied with specified User Information
- Have a signed EC Declaration of Conformity

The conformity assessment requires an EMC assessment that results in technical documentation that demonstrates that the product complies with the protection requirements, for all of the operational modes of the product and in all of its intended configurations. The EMC Assessment should assess the electromagnetic environment normally expected at the user location, taking into account the likely proximity to sensitive equipment that the product's emissions could interfere with and the likely electromagnetic threats that could interfere with the product. It should also define EMC specifications for the product and design it accordingly, taking account of component tolerances and variations in assembly and installation. Finally it will verify the EMC

design against the EMC specifications using a range of techniques including EMC testing.

EMC Directive, 2004/108/EC has two “routes to conformity.” The first is for the product to pass all of the relevant harmonised EMC test standards, although simply complying with the standards might not ensure compliance with the protection requirements in real-life operation. Manufacturers are under no obligation to apply any of the harmonised EMC test standards, or they might prefer to apply them but feel that some parts of them are cost prohibitive or neither relevant nor suitable for the product. This is the main argument for PLT as the modem and the associated mains wiring cannot be placed in an EMC test chamber. The alternative conformity route for products that are too large for a test method in a harmonised standard is to test in-situ. Annex III of 2004/108/EC describes a procedure in which a “Technical Documentation File (TDF)” in line with other EU directives is produced and is assessed by a “Notified Body”, whose report is then included with that technical documentation. The manufacturer, or his authorised representative in the EU, must keep this technical documentation at the disposal of the competent authorities for at least ten years after the date on which such apparatus was last manufactured. According to Annex IV, the technical documentation must include:

- A general description of the apparatus covering the range of configurations
- A description of the procedures used to ensure compliance with the protection requirements
- Any reports from notified bodies

Documenting the procedures used to ensure EMC compliance entails describing the EMC Assessment that was carried out and consists mainly of documents created during that work. If conformity was based on testing to all of the relevant harmonized

EMC standards, then this could simply be the test reports. But, when following the alternative route, more detailed documentation is required, for example:

- Technical arguments such as calculations, models and simulations
- Results of any EMC testing in design, manufacture, installation or operation (including non-standard methods)
- Any reasonable limitations to use agreed with the customer and/or described in the user manuals (keeping a safe distance to transmitting equipment).

The harmonised standards as a minimum aim to characterise the following:

- The radiated emission from a unit
- The conducted emission from a unit
- The radiated susceptibility of a unit
- The conducted susceptibility of a unit
- Other specific properties depending on environment

For PLT, although each of the five categories above apply, the major contention is associated with the radiated and conducted emission and the remainder of this chapter will focus on these.

3.3.2 Conducted or Radiated Emissions?

The fundamental problem for PLT in relation to EMC compliance is that the legacy and existing standards (EN 55022 in the EU) measure interference along the mains cable as a conducted emission at the PLT frequency of operation. For example a standalone PC that was being measured for CE compliance would measure the conducted emission on its mains cable below 30MHz and measure its radiated emission using an antenna for frequencies above 30MHz. The conducted emission of the standalone PC along the mains cable would be unintentional whereas the conducted emission along the PLT mains cable is intentional. Furthermore, to provide the signal to noise ratio that PLT requires to maintain a sufficient data rate, the injected level would be significantly

outside of the scope of most standards. For example EN 55022:2006 which is applicable to Information Technology Equipment (ITE) sets limits as follows:

“Limits for conducted disturbance at mains terminals and telecommunication ports:

The equipment under test (EUT) shall meet the limits in tables 1 and 3 or 2 and 4, as applicable, including the average limit and the quasi-peak limit when using, respectively, an average detector receiver and quasi-peak detector receiver and measured in accordance with the methods described in clause 9. Either the voltage limits or the current limits in table 3 or 4, as applicable, shall be met except for the measurement method of C.1.3 where both limits shall be met. If the average limit is met when using a quasi-peak detector receiver, the EUT shall be deemed to meet both limits and measurement with the average detector receiver is unnecessary.

If the reading of the measuring receiver shows fluctuations close to the limit, the reading shall be observed for at least 15 s at each measurement frequency; the higher reading shall be recorded with the exception of any brief isolated high reading which shall be ignored.”

Limits of mains terminal disturbance voltage

Frequency range MHz	Limits dB(μV)	
	Quasi-peak	Average
0.15 to 0.50	79	66
0.50 to 30	73	60
NOTE – The lower limit shall apply at the transition frequency.		

Table 1: limits for conducted disturbance at the mains ports of class A ITE

Frequency range	Limits dB(μV)	
MHz	Quasi-peak	Average
0.15 to 0.50	66 to 56	56 to 46
0.50 to 5	56	46
5 to 30	60	50
NOTE 1 – The lower limit shall apply at the transition frequencies. NOTE 2 – The limit decreases linearly with the logarithm of the frequency in the range 0.15 MHz to 0.50 MHz.		

Table 2: limits for conducted disturbance at the mains ports of class B ITE

Limits of conducted common mode (asymmetric mode) disturbance at telecommunication ports

Frequency range	Voltage limits dB (μV)		Current limits dB (μA)	
MHz	Quasi-peak	Average	Quasi-peak	Average
0.15 to 0.5	97 to 87	84 to 74	53 to 43	40 to 30
0.5 to 30	87	74	43	30
NOTE 1 – The limits decrease linearly with the logarithm of the frequency in the range 0.15 MHz to 0.5 MHz. NOTE 2 – The current and voltage disturbance limits are derived for use with an impedance stabilization network (ISN) which presents a common mode (asymmetric mode) impedance of 150 Ω to the telecommunication port under test (conversion factor is $20 \log_{10} 150 / I = 44$ dB).				

Table 3: limits of conducted common mode (asymmetric mode) disturbance at telecommunication ports in the frequency range 0.15 MHz to 30 MHz for class A equipment

Frequency range MHz	Voltage limits dB (μV)		Current limits dB (μA)	
	Quasi-peak	Average	Quasi-peak	Average
0.15 to 0.5	84 to 74	74 to 64	40 to 30	30 to 20
0.5 to 30	74	64	30	20

NOTE 1 – The limits decrease linearly with the logarithm of the frequency in the range 0.15 MHz to 0.5 MHz.

NOTE 2 – The current and voltage disturbance limits are derived for use with an impedance stabilization network (ISN) which presents a common mode (asymmetric mode) impedance of 150 Ω to the telecommunication port under test (conversion factor is $20 \log_{10} 150 / 1 = 44$ dB).

NOTE 3 – Provisionally, a relaxation of 10 dB over the frequency range of 6 MHz to 30 MHz is allowed for high-speed services having significant spectral density in this band. However, this relaxation is restricted to the common mode disturbance converted by the cable from the wanted signal.

Table 4: limits of conducted common mode (asymmetric mode) disturbance at telecommunication ports in the frequency range 0.15 MHz to 30 MHz for class B equipment

As can be seen from tables 1 to 4 (as referenced in EN55022:2006) there are two separate allowable limits for ITE, namely Class A and Class B. The difference is that Class A has a lower limit and comes with a specified warning explaining that it is Class A complaint only. Within each class there are specific limits for the mains port and the telecommunications port. Tables 1 and 2 refer to the unintentional radiation onto the mains port and tables 3 and 4 refer to the telecommunications port. The telecommunications port is defined as:

“ports which are intended to be connected to telecommunication networks (e.g. public switched telecommunication networks, integrated services digital networks), local area networks (e.g. Ethernet, Token Ring) and similar networks”.

The difficulty in defining EMC test procedures however arises with PLT modems because the telecommunications port and the mains port are one and the same. Radiated measurements are measured from 30MHz to 1GHz using the standard CISPR 16-1 methodology that will be described later.

3.3.3 Radiated emissions

The unfortunate mains/telecommunications port dichotomy associated with conducted emissions leads to the inevitable consequence that if a complaint is made the regulatory authorities have to take some enforcement action. This has made electrical distribution companies reluctant to roll out PLT on any significant scale because there are no enforcement standards that adequately cover the frequency range of PLT. There are various compliance standards and test methods that could be applied during enforcement and an outline of these is given below in order that the reader can be fully familiar with any terminology that may be encountered. The following paragraphs attempt to encapsulate the measurement factors that can be applied to a radiated measurement and are derived from best practice developed by standards bodies over many years. It should be remembered that most EMC apparatus is comparatively small and its frequency of operation allows for field measurement in some type of controlled area.

3.3.4 Detectors

Most generic spectrum analysers have a range of detection types (peak, quasi-peak, average, RMS) depending upon their application. CISPR 16-1 defines specific detector functions and performance that measuring apparatus must incorporate as part of the CISPR 16-2 measurement methodology. The most familiar detector type is an RMS detector which when a signal is sinusoidal will represent $\frac{1}{\sqrt{2}}$ of the maximum value. When signals are sinusoidal in nature the RMS and therefore peak values are of some use because they provide a predictable signal level against which potential interference can be measured. If, however the interference signals are spurious in nature then the relationship between peak and RMS is not straightforward to measure. Against the backdrop of the radiated measurement which is in relation to interference to radio services, it is useful to know how spurious or non-sinusoidal signals would affect a victim receiver.

The most commonly used detector in radiated measurements is therefore the quasi-peak detector. It is used in EMC measurement because it is believed to be more representative of the “annoyance” effect that a victim receiver may perceive. A quasi-peak detector for EMC measurement is similar to a peak detector followed by a lossy integrator. The peak detector is a rectifier followed by a low-pass filter to extract a baseband signal consisting of the slowly (relative to the receiver centre frequency) time-varying amplitude of the impulsive oscillation. The integrator has a rapid rise time and longer fall time, so the measured output for a sequence of impulses is higher when the pulse repetition rate is higher. The quasi-peak detector is calibrated to produce the same output level as an average-power detector when the input is a continuous wave tone in the receiver bandwidth. Quasi-peak detector readings will always be less than or equal to the peak detection. Because quasi-peak readings take longer, (by 2 or 3 orders of magnitude compared with peak) it is very common to scan initially with the peak detection first, and then if this is marginal or fails, switch and run the quasi-peak measurement against the limits. The parameters (bandwidth, charge time, discharge time, mechanical time constant, overload factor) associated with a quasi-peak detector vary with frequency and are defined in CISPR 16-1.

The other frequently used detector is the average detector. The average detector is required for some conducted emissions tests in conjunction with the quasi-peak detector. Also, radiated emissions measurements above 1 GHz are performed using average detection. The average detector output is always less than or equal to peak detection. Average detection is similar in many respects to peak detection. For average detection to take place, the peak detected signal must pass through a filter whose bandwidth is much less than the resolution bandwidth. The filter averages the higher frequency components, such as noise at the output of the envelope detector.

There are other analyser properties such as sensitivity and selectivity but they tend not to vary between the different measurement techniques and will not be discussed further. The assumption from herein is that the analyser used to undertake the measurement is in accordance with CISPR 16-1.

3.3.5 Antenna Type

As discussed earlier the type of antenna is dependent on whether the source to be measured is fundamentally electric or magnetic in nature. Monopole antennas can be used in the far field but they tend not to be sensitive enough to pick up PLT measurements at large distances. For almost all enforcement standards and papers on PLT radiated measurements, the general assumption is that a loop antenna is used. Loop antennas which measure the magnetic field component convert it to a current and therefore the output is in dB μ A/m. As previously mentioned, it is inappropriate to convert this to an equivalent electric field strength unless the measurement is taken in the far-field. There are various types of loop antenna on the market that comply with CISPR 16-1. Standard loop antennas tend to lack sensitivity at lower frequencies due to their dimensions relative to the wavelength and therefore they are often amplified or have tuned elements. For small EUTs, CISPR 16-1 has a special procedure for a 3 axis Large Loop Antenna (LLA) which surrounds the EUT in 3 axes. This is of course of no value for PLT measurements.

The other key factor that can change the measured result is the orientation of the antenna which is affected by the environment and whether one is in the near field. The harmonised standard will specify the orientation of the antenna and some military standards that, by necessity, measure in the near-field, recognise the inherent inaccuracy and measure 3 axes to produce the RMS value. Nevertheless most standards adopt an azimuthal orientation which generally maximises the reading for a single orientation, particularly when the distance is greater than the size of the

apparatus . The height is also adjusted between 1m – 4m to the centre of the loop to obtain the maximum signal strength. This continual change of orientation makes the automation of radiated measurements difficult particularly in the near-field where the magnetic field is complex in nature and other orientations are required.

3.3.6 Distance

The other key variable of measurements is distance. This can range from 1m to 30m depending on whether the standard is for compliance or enforcement. Most standards recommend between 3m and 10m with 10m being the preference unless ambient noise is such that the measured interference cannot be detected. Some military standards have special procedures for very near-field measurements but they are indicative and make no claim to an actual value being read. Equally, FCC measurements are taken out to 30m which, in the case of PLT frequencies, would appear a more appropriate distance (signal strength notwithstanding).

3.3.7 Location

The preferred location for all EMC measurements is where the environment is well defined and the ambient noise can be negated. For small EUT with a maximum dimension of less than a few metres the preferred location would be in an anechoic chamber that has little or no ambient magnetic field. This of course is not feasible for large structures and therefore the best solution is in an OATS. An OATS would normally have a ground plane installed such that reflections are predictable and the Normalised Site Attenuation (NSA) can be calculated. CISPR 16-2 states that these are only applicable for measurements from 30MHz – 1GHz, as it is generally accepted that lower frequency emissions are conducted. The field attenuation can therefore be measured and the OATS calibrated by taking measurements at set distances to determine the normalising factor to be applied when the actual measurements are made. Again for PLT the dimensions are too large that there is no option but to

measure in-situ. CISPR 16-1 accommodates in-situ measurements, but they are intended to provide evidence that the total system in-situ complies with a harmonised standard. The TDF would be written for that individual system and the ground planes and surrounding environment duly noted. In the case of PLT, however, it is not feasible to measure at one site and attempt to correlate the measurements with another site.

3.3.8 Antenna Factor

The antenna factor reflects the fact that an antenna is being used as a measuring device. Each antenna is calibrated by the manufacturer and a datasheet is supplied that explains the attenuation factor that should be applied to any radiated measurement made with the antenna. The calibration data will be at specific frequencies and CISPR 16-4 explains how interpolation of frequencies that are not supplied should be calculated. It further explains how the height and distance of the antenna from the calibrated baseline should be adjusted. It is worth stating that most of the guidance is associated with normalisation of the OATS to obtain a firm understanding of the field attenuation.

3.3.9 Artificial Mains Network

Although not wholly applicable to radiated measurements it is worth mentioning a piece of test equipment that has caused some confusion in a few PLT papers. CISPR-based standards require a conducted emissions measurement on the mains port and unless the products to be tested are exclusively battery-powered an Artificial Mains Network (AMN) or Line Impedance Stabilising Network (LISN) is essential. The purpose of the AMN/LISN is to offer a defined radio frequency impedance to the mains terminal of the EUT and to provide a defined coupling route from the EUT to the measuring instrument. Coupling from the AMN/LISN to the spectrum analyser should be via a transient limiter to protect the analyser's input.

3.3.10 Measurement Errors

The final and most critical aspect of EMC measurement is to understand the errors associated with the measurement being undertaken. In almost all literature on PLT measurement a treatment of errors is not given in relation to the quoted results. Authors will quote results to the nearest dB μ V/m but will make no assertion about the errors associated with the measured quantity.

CISPR 16-4 defines the parameters of uncertainty that as a minimum must be accounted for when making measurements and must be quoted in the test report. It further explains the uncertainty budget and how it should be dealt with in the test report. It does however assume that all measurements below 30MHz are conducted and all measurements above 30MHz are radiated. Nevertheless, the range of acceptable errors of an EMC test site is between 3.6dB – 4.5dB in the range 9kHz to 300MHz - and this should be a good indicator of the level of errors that can be expected. For radiated emission measurements the following parameters should be accounted for when measuring in an OATS or alternative site:

- Receiver reading
- Attenuation of the connection between antenna and receiver
- Antenna factor
- Receiver sine-wave voltage accuracy
- Receiver pulse amplitude response
- Receiver pulse response variation with repetition frequency
- Receiver noise floor
- Mismatch effects between antenna port and receiver
- Antenna factor frequency interpolation
- Antenna factor variation with height
- Antenna directivity

- Antenna phase centre
- Antenna cross-polarisation response
- Antenna balance
- Test site
- Separation between equipment under test and measurement antenna
- Height of table supporting the equipment under test

Further details of each can be found in CISPR 16-4, but for each parameter a value for the level of uncertainty is quoted and applied to a probability distribution function which leads to the values of 3.6dB – 4.5dB. The purpose of listing these is to highlight to the reader that radiated measurement for compliance is highly variable and if measurements are taken in-situ, the variation is wider because there is no normalised site attenuation data to give confidence to measurements. The expectation is that all measured values should be quoted with an associated error and compliance based on the error adjusted measured value. If one remembers the arguments made earlier regarding the uncertainty due to measurement in the near-field whilst applying far-field correction factors (i.e. assuming that $Z_0 = 377\Omega$ and E and H are related by 51.5dB), then one would expect radiated measurements to have significant errors.

3.4 COMPARISON OF STANDARDS AND METHODS

The final topic in this chapter is to highlight some common harmonised standards, regulatory test procedures and other PLT related procedures to provide an overview in the variation of the methodology and associated limits. Furthermore, there may be some utility in other standards that will apply to PLT that could be used in setting a new procedure and limit. Interestingly, a search of commercial EMC standards highlighted more than 400 different examples related to EMC design and measurement.

3.4.1 EMC Standards

CISPR 22 (EN55022:2006 in the EU or BS EN 55022:2006 in the UK) is the harmonised standard for compliance of Information Technology Equipment. As previously discussed, it classifies equipment as being either Class A or Class B depending on the environment and the level of compliance. Class B equipment is intended to be used in the domestic environment where its location may not be fixed and therefore it has more stringent compliance levels applied. Class A therefore carries the warning *"This is a Class A product. In a domestic environment this product may cause radio interference in which case the user may be required to take adequate measures."* It has two main tests. In the frequency range 150kHz to 30 MHz disturbance is considered to be conducted and measurements are taken on the mains and telecommunications ports. An AMN/LISN is specified for both mains and telecommunications ports and the configuration defined in detail. The measurement is taken both as quasi-peak and average unless the average limit is met by the quasi-peak detector in which case the test does not have to be undertaken. The second test is the radiated disturbance test and is to be used when measuring frequencies in the spectrum 30MHz to 1GHz. The detector is set to read-quasi-peak. The antenna should be a balanced dipole and be resonant in length above 80MHz. The measurement distance is made at 10m, however if the field strength measurement cannot be made because of high ambient noise it can be moved closer and a conversion factor of 20dB per decade should be applied. *"Care should be taken at frequencies near 30MHz due to near-field effects"*. The antenna should be adjusted between 1m and 4m to obtain the maximum reading at each frequency. The antenna also should be varied in azimuth and in polarisation to obtain the maximum field strength reading. The site and ground planes are in accordance with CISPR 16-1 and are tightly controlled. Annexes provide indicative diagrams of each method as well as how to determine site characteristics if those are not already known. In summary, CISPR 55022:2006 is a perfectly adequate

standard for most ITE. However, as mentioned previously, PLT intentionally sends data traffic onto the mains port and compliance can therefore not be met without a severe degradation of performance.

CISPR 11:2009 (EN 55011:2009 in the EU and BS EN 55011 in the UK) is broadly similar to CISPR 22 but applies to Industrial, Scientific and Medical (ISM) radio frequency equipment. It identifies equipment as being in groups depending on whether the equipment intentionally conductively couples energy as part of its purpose or whether it intentionally radiates energy as part of its purpose. This is because the standard is primarily associated with intentional transmitters. As with CISPR 22, there are different Classes of equipment depending on the environment and it recognises that some medical equipment is specialist and allows it to be measured in-situ. Unlike CISPR 22 it has a radiated measurement from 150kHz to 30MHz taken at 10m. The previous version of the standard took this measurement at 30m, but test facilities were having trouble taking the measurement due to high ambient noise. The conformance limit is stated in dB μ A/m and is measured using a quasi-peak and average detector at a distance of 10m. Specific allowances are made for in-situ testing.

FCC Part 15, or more correctly Title 47 of the Code of Federal Regulations (FCC) Part 15 is a set of regulations that apply to equipment that is produced or imported into the United States of America. Although the FCC is strictly a regulatory body they have authority for compliance. The standard includes intentional and unintentional radiators and is therefore detailed by definition. For the purpose of this discussion the frequency range 1.7-30MHz will be considered. Equally, as with other standards, there are Class A and Class B limits depending upon the operating environment and type of equipment. For unintentional radiators, all testing below 30MHz is undertaken as conducted disturbance testing and the values are similar to CISPR 22. For intentional radiators there is additional radiated disturbance testing using ANSI C63.4-1992 at a

specific distance of 30m. At this distance the maximum value is 30dB μ V/m measured with a loop antenna and converted using the free space conversion factor. There are also specific operational frequencies at which the limit must be protected and should not be used by intentional radiators.

Mil-Std 461/462 are probably the most comprehensive set of EMC test standards. They accommodate legacy standards adopted by the United States Army, Air Force and Navy and recognise the difficult task of EMC compliance in highly complex aircraft and other military vehicles which are constrained for space. During the awarding of the contract, the procuring office will identify and agree which parts of the standard are applicable and an agreed test plan would be drawn up. A summary of some of the tests will be given here as an indication of testing in the frequency range 1.6-30MHz. Test Method RE02 and RE05 measure radiated disturbance from 14kHz to 10GHz using a bi-conical and a monopole antenna in both horizontal and vertical polarisation at a 1m distance. There are additional radiated measurements for spurious and harmonic emissions as well as specific measurements for high voltage power lines. The measured limits are in dB μ V/m.

In summary, the standards above (and others not discussed here) define test methods and limits and are based on a balance between time to test and the likely environment that a product will see when it is in service. They are for the purpose of compliance before deployment.

3.4.2 Regulatory Standards

In addition to compliance standards, many countries have a standard for the protection of radio services. If a complaint is made a test regime is used to determine the level of interference. The following regulations define test methods and acceptable limits of interference once a product has been deployed and is causing a disturbance.

MPT 1570 is the UK regulatory procedure and was used by OfCom. It only applies in the frequency range 9kHz – 1.6MHz. As no standard in the range 1.6 – 30MHz exists a draft was produced but never approved. Furthermore, in a written statement to Parliament (Timms 2003), the Minister for Energy revoked MPT1570's status as a regulatory standard, but as it was the basis for much of the early debate on PLT and is still quoted by authors it is mentioned here. The procedure involves using a CISPR 16-1 compliant loop antenna and receiver. The antenna is placed at any distance not closer than 1m from the premises and on a tripod 1m high. It should be placed in multiple locations with different orientations to obtain the highest measurable signal. Limits are expressed in dB μ A/m.

REGTP NB30 is the German Regulatory standard. It was the first standard to attempt to set a limit for PLT and therefore is worthy of mention. It is still quoted in publications associated with PLT as it was seen as a good compromise between an EMC standard and a regulatory standard. Measurements are taken at a 3m distance with a 60cm loop antenna 1m high. The detector is a peak detector and the limits are quoted in dB μ V/m with conversion using the far-field free space conversion factor.

Other limits have been proposed, with many being quoted in the early discussions on PLT limits. There are various papers by the BBC on the limits that would protect radio services and the methodology to be employed. The other commonly discussed limit is the "Guellemann limit" (see chapter 2). It discussed the attenuation with distance of a magnetic field and made recommendations of how equipment connected to the mains should be regulated. It is understood to have been used in the derivation of the NB30 limit. Figure 3-15 shows a comparison of various standards and recommendations that have been normalised for distance using the far-field 1/r extrapolation factor. The far-field adjustment of 51.5dB is also used to convert all values to dB μ V/m and a

conversion factor is added to bring all values to their peak values. No firm conclusion should be drawn from this as the extrapolations are inaccurate but it is clear that there is significant variation in proposed limits depending on whether the limit is a compliance or a protection limit.

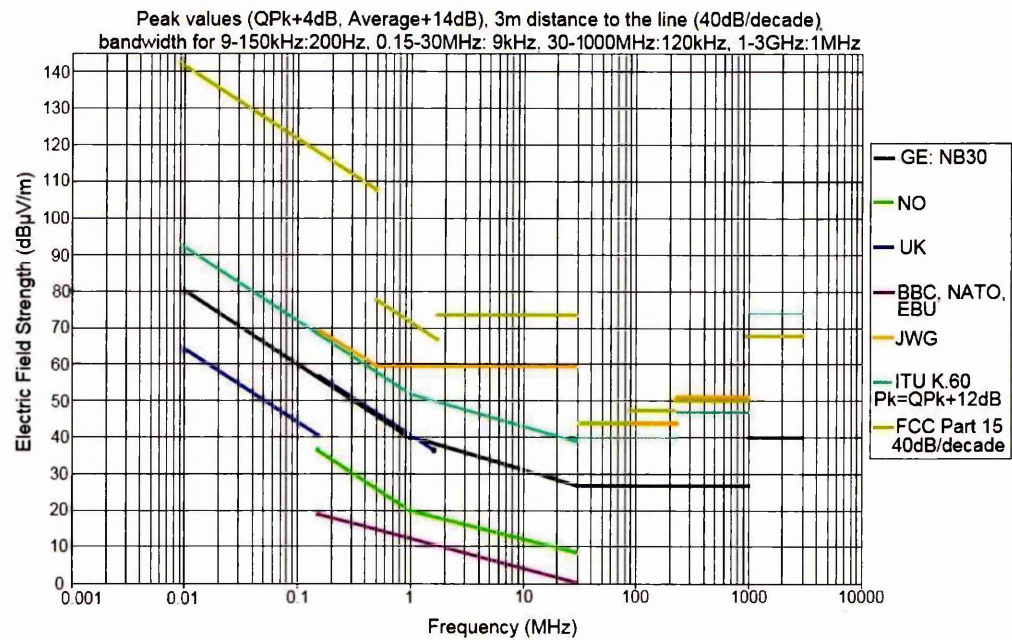


Figure 3-15 – Comparison of EMC limits⁸

3.5 SUMMARY

In this chapter PLT technology has been discussed in detail. The theory behind electromagnetic radiation has been presented along with an overview of EMC measurement and associated standards. There is, however, significant tension between those that wish to roll out PLT and those that may be affected by it. Modern manufacturers and electrical distribution companies make the argument that the compliance standard CISPR 22 does not cater for a common mains and telecommunications port within the conducted emission section, and therefore apply the second route to conformity and present a case in a TDF. A further complexity has arisen because the previous version of the standard could be used before 1 Oct 2009. The later version of the standard must now be used, which effectively forces the PLT

⁸ Courtesy of NATO

manufacturers to comply with the mains limits and therefore the TDF route is now difficult to argue. This has increased the importance of reaching an agreement on a radiated emission standard for PLT.

The main objective of standardisation bodies in the last ten years has been to agree a standard but to date none have been published. Various authors have attempted to produce an agreed limit, but many of the assumptions made in deriving these limits apply only to the far-field and cannot be used without a caveat explaining the associated errors. In chapter 4 a range of measurements will be undertaken that aim to provide a greater understanding of these errors and also to provide a better understanding on the effects of PLT. An alternative measurement method that is used in military aircraft EMC testing will be discussed in relation to its applicability to PLT.

CHAPTER 4 - MEASUREMENTS

4.1 BACKGROUND

As previously explained the issue that is preventing an accelerated roll out of PLT systems is an acceptable regulatory limit that both manufacturers for PLT modems and electrical power distribution companies can be confident in complying with. To achieve this some researchers have used theoretical prediction and others modelled prediction. The key research in the last five years has been in the area of measurements. This has been limited due to a lack of distributed PLT systems, however the PSCRG was provided an opportunity to visit some new trial sites in 2005 and undertake a measurement campaign. Furthermore, additional measurements were required to confirm some assertions made by other researchers (affects on distance and orientation) and also to better correlate the radiated signals to the effects on radio services by PLT. This chapter discusses these measurements and the associated methodology in detail.

4.2 MEASUREMENTS

The measurements that had previously been undertaken by other researchers were limited to a snapshot of a single PLT network at a single location in various countries around the globe. The PSCRG were fortunate to be represented on the CISPR I committee and were invited to undertake and witness various trials in the UK, Europe, USA and Australia. This allowed the group to collate results across many networks and the results will be published in full by the group during 2012, however in the meantime an abridged version is introduced in paragraph 4.4. There were specific measurements that were undertaken to better understand the measurement techniques, accuracy of other researchers' results and to supplement other researchers' results (which concentrated mainly on the measurement of electric field strength to determine whether or not interference was likely).

In addition to the radiated field measurements being undertaken by the group a number of new measurements were undertaken with the following aims:

- To obtain an understanding on the effects of antenna type and position on radiated emissions from PLT.
- To clarify the assumption that attenuation with distance is $1/r$
- To provide an estimate of where the near-field/far-field boundary is for PLT systems
- To determine whether the principles of mutual interference testing adopted by the military could be used to determine coexistence of PLT and radio services
- To determine if there is a correlation between signal ingress and the “K factor” of the PLT network.

4.3 ACCURACY AND UNCERTAINTY

The application of accuracy and uncertainty in EMC compliance measurements was discussed in detail in chapter 3, using CISPR 16-4-2 as the source document. The basic principle of EMC measurement uncertainty is that EMC standards define what is to be measured (measurand) and define a method to measure it. The measurement process is, however, complex and imperfect and as a result there are errors that mean that the measured result is only an approximation of the true value. This value is only considered valid for compliance purposes when accompanied by a statement of uncertainty. Overall uncertainty is defined by Equation 4-1 as:

$$U_c(y) = \sqrt{\sum_{i=1}^m U_i^2(y)} \quad (4-1)$$

Where:

$U_c(y)$ is the combined uncertainty of m contributions of each uncertainty $U_i(y)$.

The underlying assumption of CISPR 16-4-2 is that a reasonable assessment of uncertainty can be accommodated in measurement results because the tests are undertaken either in an anechoic chamber or at the very least on a calibrated OATS. In chapter 2 while discussing measurements by others, it was apparent that the treatment of risk in the main is ignored in the presentation of results. Results are presented with a high degree of accuracy, with no adjustment to the data or indeed a statement of the uncertainties involved. The key reasons for this are that measurements are taken in non-calibrated sites, in areas where the measuring equipment is not optimised for use (the near-field) and therefore the calibration data associated with the equipment is incorrect. Equally, because there is no shielding from the background noise, it is difficult to determine whether measured values are due to PLT signals or ambient noise. Finally, the guidance assumes that all measurements below 30MHz are conducted emissions and therefore the uncertainty does not take account of measurement uncertainty in the near-field. The correct application of uncertainty in EMC measurements in accordance with CISPR 16-4-2 for general radiated measurements requires that the parameters discussed in chapter 3 are accounted for, summed and added to the measurand. If, in the case of in-situ PLT measurements, where the calibration factors cannot directly be applied, then an alternative should be undertaken to at least make an indicative statement of measurement uncertainty.

Recognising that it is imperative to make a statement of uncertainty but also impractical to follow the guidance of CISPR 16-4-2 for in-situ PLT measurements, alternative methods were investigated to provide an indicative assessment. The aim of the chosen method would be to apply statistical techniques to subjective quantities as this would offer an uncertainty budget that approached the CISPR 16-4-2 methodology. This was seen as an improvement on other research that has taken no account of uncertainty whilst operating with the limited uncertainty data available for in-situ measurement. The

technique chosen to accommodate the subjective elements was a simplified version of Monte-Carlo analysis.

4.3.1 Monte-Carlo Analysis

Monte-Carlo analysis is a method of analysis that uses computational techniques to run multiple simulations of a scenario and then calculate the mean occurrence of an event or events. It was originally used during the development of the US atomic bomb as a method to estimate atomic radiation shielding. The estimates at the time could not be completed with standard analytical techniques and the concept of using randomness and the evolution of early computers was developed. As the project was classified it was given the codeword (Monte-Carlo) named after similar concepts of randomness of events in gambling in Monte-Carlo casinos. Today it is used in many fields but primarily in engineering, financial management and fundamentally in project and risk management.

There are various versions of the techniques, and there are many add-ons available for programs such as Microsoft Excel but in general they follow a similar format. Firstly, a set of inputs are defined for the model. Secondly an upper and lower value for each input is defined along with a Probability Density Function (PDF) which defines for a random set of events the probability of that event occurring. Typical distribution functions in Monte-Carlo analysis are uniform (all events are equally probable), normal (the most likely probability of an event occurs around a central value and reduces in probability non-linearly from the centre), triangular (the most likely probability of an event occurs around a central value and reduces in probability linearly from the centre, and skewed triangular (the most likely probability of an event occurs off of a central value and reduces in probability linearly from that value (Figure 4-1).

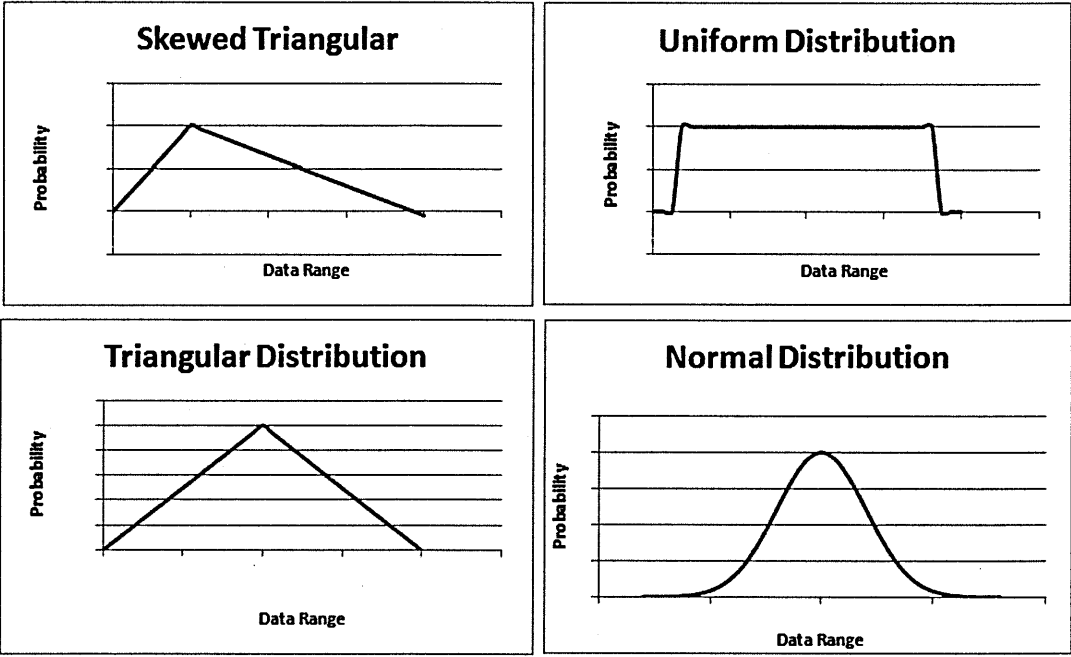


Figure 4-1 – Probability distribution functions

The Monte-Carlo simulation is run and an output is derived which takes account of the random nature of events that effect the output rather than on basic human instinct that would otherwise be applied. The simulation consists of multiple iterations of each event with the increase in iterations leading to a more consistent result. However, a compromise between the duration of simulation and overall consistency needs to be taken, particularly as the number of inputs increase.

By way of a simplified example: if one was building a house, the time spent on each activity, such as buying land, obtaining planning permission, laying foundations, building walls, attaching the roof, facilities or internal decoration can be estimated. Each activity has a duration that has a range of uncertainty associated with it and it also carries an element of risk. The uncertainty may be that it should take 7 days to dig foundations but if there were more people it could happen in 3 days or if the ground is hard it could take 10 days. There are also risks that are one-off events that have a probability and impact such as finding archaeological remains and having to cease work for some months. To obtain an estimate of the completion of the house would be

challenging but applying each risk and uncertainty as inputs to a Monte-Carlo analysis allows a deterministic completion date to be calculated based on the pseudo random nature of each set of inputs to obtain a “most likely” date. In common with other models, the result is as good as the modelled inputs.

4.3.2 Application of Monte-Carlo Analysis to PLT Measurement

To estimate the uncertainty of each measurement type, a list of each measurement uncertainty has to be applied to the input. To maintain configuration control it is good practice to list these as a set of master assumptions in order that future tests can be repeated, and also once the results have been analysed the underlying data is understood. Table 4-1⁹ and Table 4-2 show a list of uncertainties, the overall derived uncertainty budget and for each uncertainty an explanation of the underlying assumption. The expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor $k = 2$ for a level of confidence of 95% which is the standard coverage factor for industrial and commercial measurement applications as defined by CISPR 16-1. $k=1$ equates to 68%. This results in an overall uncertainty of 8.5dB.

⁹ Template Courtesy of Schaffner EMC products

Uncertainty	Value (dB)	PDF	Divisor	Ui(y)	Ui(y)^2
Receiver Reading	0.100	Uniform	1.732	0.058	0.003
Cable Loss	0.100	Normal	2.000	0.050	0.003
Receiver Sine wave Accuracy	1.000	Normal	2.000	0.500	0.250
Receiver Pulse Amplitude	1.500	Uniform	1.732	0.866	0.750
Receiver Pulse Repetition Rate	1.500	Uniform	1.732	0.866	0.750
Noise Floor Proximity	0.000	Normal	2.000	0.000	0.000
Antenna Factor Calibration	0.000	Normal	2.000	0.000	0.000
Antenna Directivity	0.200	Uniform	1.732	0.115	0.013
Antenna Factor Height Dependence	2.000	Uniform	1.732	1.155	1.333
Antenna Phase Centre Variation	0.000	Uniform	1.732	0.000	0.000
Antenna Factor Frequency Interpolation	0.250	Uniform	1.732	0.144	0.021
Cross Polarisation Balance	0.100	Uniform	1.732	0.058	0.003
Measurement Distance Variation	2.000	Uniform	1.732	1.155	1.333
Site Imperfections	8.000	Triangular	2.449	3.267	10.671
Frequency Step Error	0.000	Uniform	1.732	0.000	0.000
Mismatch	-2.000	U-shaped	1.414	1.414	2.001
Measurement System Repeatability	4.000	Normal	1.000	1.000	1.000
Combined Standard Uncertainty				4.258	18.132
Expanded Uncertainty		k=	2.000	8.516	

Table 4-1 – List of uncertainties in chapter 4 measurements

Uncertainty	Assumption
Receiver Reading	Determined by least digit fluctuation
Cable Loss	Attenuation from antenna to receiver
Receiver Sine Wave Accuracy	From manufacturers specification
Receiver Pulse Amplitude	From manufacturers specification
Receiver Pulse Repetition Rate	From manufacturers specification
Noise Floor Proximity	Can be ignored as measurements are well above noise floor
Antenna Factor Calibration	Can be ignored as included in measurement file otherwise as calibrated
Antenna Directivity	Not significant for loop antenna
Antenna Factor Height Dependence	Derived from general practical experience or other similar measurements
Antenna Phase Centre Variation	Not applicable to loop antenna
Antenna Factor Frequency Interpolation	Between entries in the frequency table
Cross Polarisation Balance	Not significant for loop antenna
Measurement Distance Variation	high as 1/r cannot be assumed
Site Imperfections	high as not a calibrated OATS - standard would be 4 dB
Frequency Step Error	0 for manual 1dB for auto
Mismatch	Receiver + antenna Voltage Reflection Coefficients from specifications
Measurement System Repeatability	4 times normal due to variability of test set locations
Combined Standard Uncertainty	Square root of the sum of all $U_i(y)^2$

Table 4-2 – Assumptions for chapter 4 measurements

4.3.3 Antennas

In 2000, OfCom (then the Radio Communications Agency) tasked the University of Hertfordshire with designing a high sensitivity antenna that could measure electric field strengths of $1\mu\text{V/m}$ ($0\text{ dB}\mu\text{V/m}$). The final design was a set of three H field antennas (Figure 4-2) that could measure an equivalent electric field under far-field conditions. It was perceived, at the time, that for the protection of services measurements would be required that were similar to the field strengths that the amateur radio community would receive. These loop antennas were provided to the PSCRG and it was the intention to use these highly sensitive antennas to improve the accuracy of any radiated emission results at low power levels.

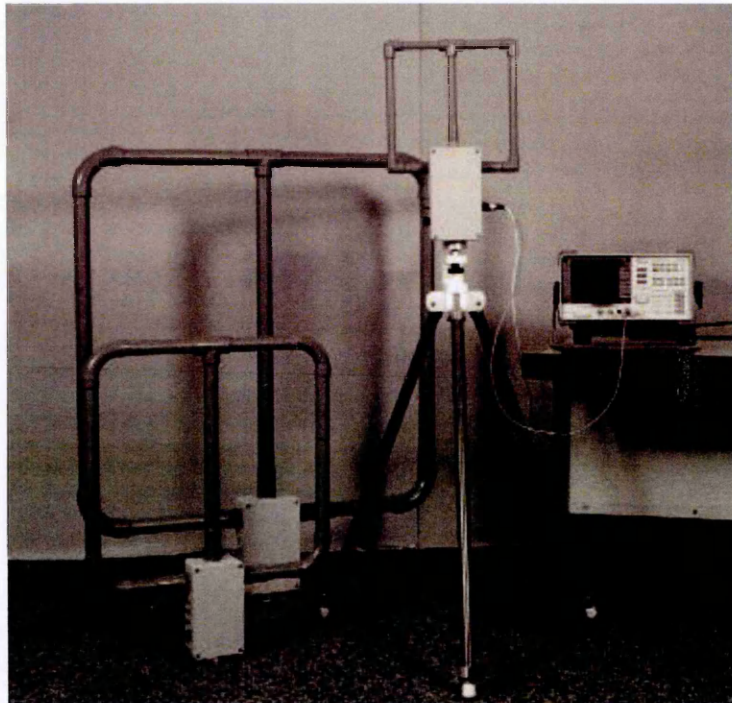


Figure 4-2 – University of Hertfordshire tuned antennas

Each antenna has to be tuned manually at each measurement frequency and there are different antennas for different parts of the HF band. During each measurement, the EMC receiver has to be tuned to the frequency of interest then the antenna tuned. It is therefore not possible to run a frequency sweep at each measurement distance. As will be seen later even manually tuning just the EMC receiver with a standard loop antenna is time consuming and therefore as the following measurement campaign was

attempting to measure the radiated field at many distances, frequencies, powers and antenna orientations, the antennas were not used.

One of the aims of the research was to ensure that any measurement technique was repeatable by a number of researchers. The chosen antenna was a CISPR 16-1 calibrated EMC antenna, a Schaffner HLA 6120. It is an active antenna that has a preamplifier that matches the very low impedance of the loop to the receiver. It covers the range 9kHz – 30MHz and has an acceptably flat antenna factor across the entire range. It is designed for CISPR 11 and 16 swept radiated measurements and is commercially available for other researchers to procure. It is recognised that in comparison to the tuned antennas the noise floor is higher and very small signal levels that could be measured with tuned antennas cannot be measured with antennas that respond to the PLT HF band. This however was an acceptable compromise because earlier measurement campaigns by other researchers demonstrated that PLT signals are always above the antenna noise floor even when measured at 30m. In sacrificing sensitivity for repeatability it is recognised that additional error has been introduced but where necessary this has been recognised and compensated for in the error budget calculations.

4.4 RESULTS OF PSCRG RADIATED EMISSION TESTS

4.4.1 Rationale

Other research has concentrated on radiated emissions tests from PLT networks in a single location. This leads to a data set that is specific to that measurement campaign and does not allow for extrapolation to other scenarios. The PSCRG main research objective was to undertake a measurement campaign to determine the correlation between different modem types, networks and geographical locations for a fixed measurement methodology. The ideal methodology would be a measurement campaign that could be repeated at each location during various times of day and

throughout the year to be more representative of network loading. In addition these would be repeated at urban, semi-rural and rural locations to allow the affect on each variable to be monitored and reported on. The limiting factor is the very limited availability of PLT networks and therefore it was concluded at the outset that a “take what one can get” approach would be adopted. This would, at least, allow a minimum and maximum range of radiated emission figures that could then be assessed. On completion of the testing the aim was to provide a typical PLT radiated level and to determine a generic probability distribution around the average or median value.

4.4.2 Technique

Since 2003, the PSCRG have undertaken over 300 different measurements associated with PLT. As mentioned in chapter 3, there are a range of radiated emission measurement techniques that can be employed and what follows has been limited to those that are similar to the OfCom test methodology to allow correlation with the OfCom results. The OfCom measurements at the SSE test sites were important because they were the only set of results taken in the UK and one of the largest global PLT networks at that time. There have been no PLT networks of an increased size rolled out globally since then. The technique is based on the MPT1570 low frequency (below 1.6MHz) measurement technique extrapolated to 30MHz. The background to the methodology is that it provides *“reasonable protection to broadcast radio receivers having integral ferrite rod antennas which are intended for use within domestic premises”*. The tests used a CISPR 16-1 compliant measuring receiver (Rohde and Schwartz ESHS-10) with a measurement bandwidth of 10kHz set to a quasi-peak response. The standard MPT1570 test, because it is used in response to a complaint of interference, uses a peak response detector. The random and high ambient noise in many test sites precluded its use for this campaign and therefore, in line with the CISPR 22 standard, a quasi-peak detector was used. The Schaffner HLA 6120 loop antenna secured on a height adjustable and rotatable tripod was used. The antenna

was set at a height of 1m from the ground plane to the base of the antenna and the antenna angled perpendicular to the premises under test. For the remainder of this chapter an antenna that is stated to be perpendicular to the premises is taken to mean that it is physically aligned 90° to the premises and an observer standing at the premises and looking towards the antenna would see a minimum surface area of the loop (in fact it would be observed as a vertical pole on top of the tripod). Equally a parallel antenna would present the maximum physical surface area to an observer standing at the premises who would perceive it to be a perfect circle. The antenna was then placed between 1m and 3m from the premises under test and the receiver was set to read frequencies from 1.6MHz to 30MHz at 50kHz increments. The results were captured as magnetic field strengths and adjusted to incorporate the antenna factor and using an H field to E field conversion factor of 51.5dB.

4.4.3 Results

A number of tests were conducted in the UK, Europe and Australia and the following specific tests have been identified as having significant points of interest that have not necessarily been highlighted in other papers to date. To obtain a general view, one location from each of the areas has been chosen and analysed.

4.4.4 Results – 1 Maidenhead, UK – ASCOM & Main.net

Figure 4-3 shows the comparison between the ambient noise and the PLT emissions at 1m. It also shows the ambient subtracted from the electric field which is not always apparent in papers on PLT.

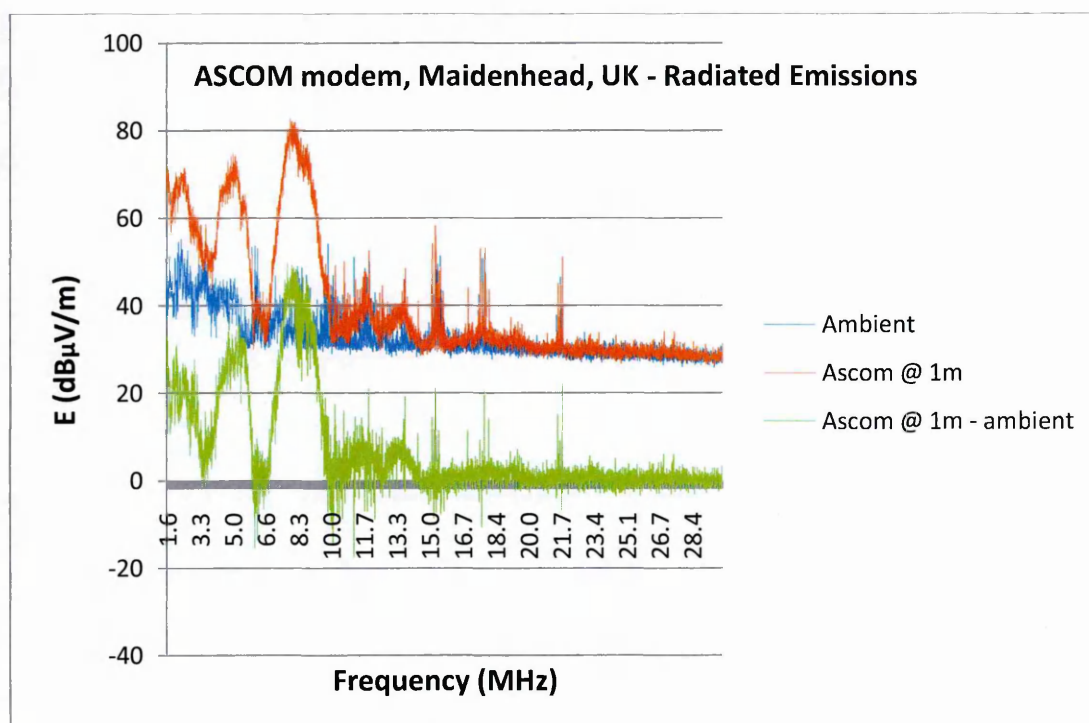


Figure 4-3 – PLT emissions at Maidenhead, UK (ASCOM)

It can be seen that the ASCOM modem, as it is an access modem, has good filtration outside of its access band and there is not a great deal of inter-modulation emissions present. It also shows a large increase of 40-50 $\text{dB}\mu\text{V/m}$ (not risk adjusted) above the noise floor in a wide portion of the HF band.

Similarly, Figure 4-4 shows a Main.net system at the same location and under the same measurement conditions. As can be seen, the Main.net system does not produce such a large increase in noise floor compared to the ASCOM system but it does affect a much wider portion of the HF band. This is as expected, because to reduce the power but deliver a similar data rate would require more bandwidth.

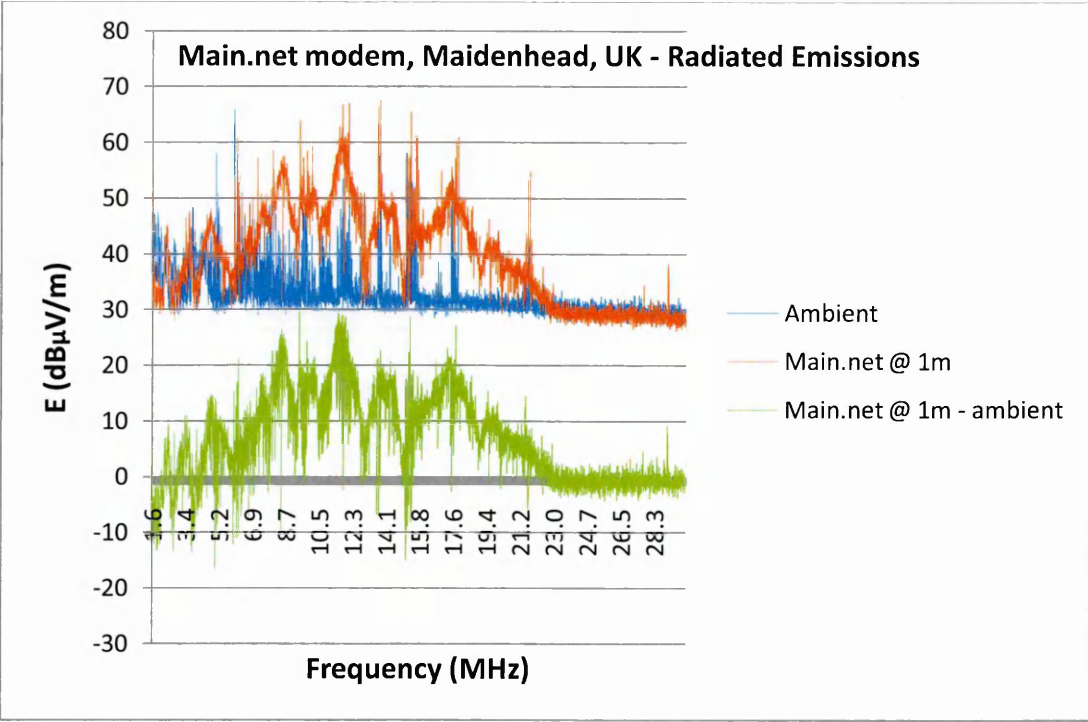


Figure 4-4 – PLT emissions at Maidenhead, UK (Main.net)

4.4.5 Results – 2 Linz, Austria – Main.net

A similar Main.net system was trialled in Linz, Austria and the results are reproduced here to show comparison of the same system but in a different location. Figure 4-5 shows the measured PLT with the ambient included.

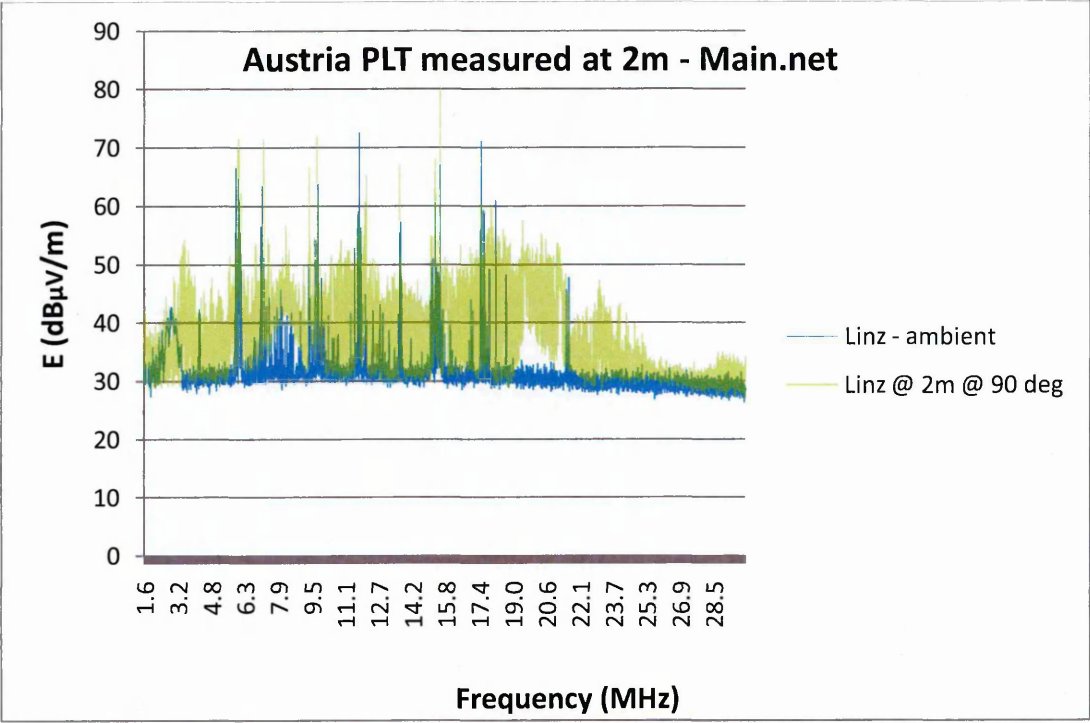


Figure 4-5 – PLT emissions Linz, Austria (Main.net)

Like the Main.net system in the UK, the radiated emissions cover much of the band. The system was notched and the test rerun with the results reported in Figure 4-6, this time with the ambient subtracted.

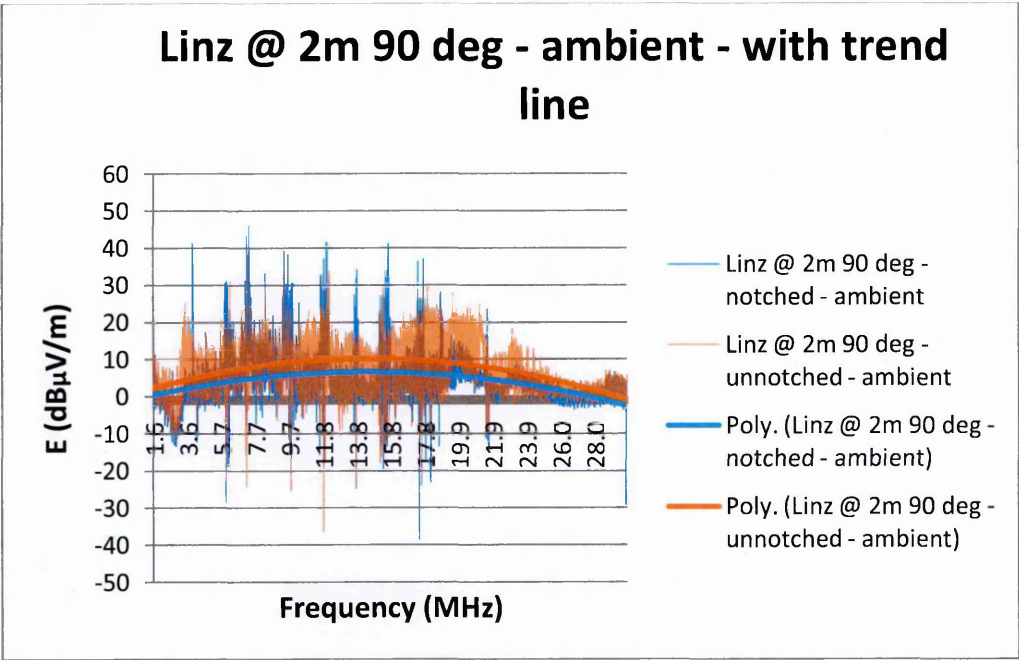


Figure 4-6 – PLT emissions Linz, Austria (Main.net) with trend line

The results are presented with ambient noise removed and for both the notched and non-notched systems. A polynomial trend line has been added to show the overall effects of notching. It can be seen that overall in the centre of the band, PLT emission increases the noise floor by 10dB μ V/m trailing off to 0 at the lowest and highest frequencies. The notching process, although useful in certain frequencies, only reduces the overall polynomial distribution by the order of 3dB μ V/m.

4.4.6 Results – 3 Canberra, Australia – DS2

The tests were repeated outside Canberra, Australia. Figure 4-7 shows the different modulation scheme that DS2 uses. It introduces an increase in the noise floor of 25–30dB μ V/m (between 1m and 3m measurements). The figure also shows the decrease in electric field as the measurement moves from 1m to 3m.

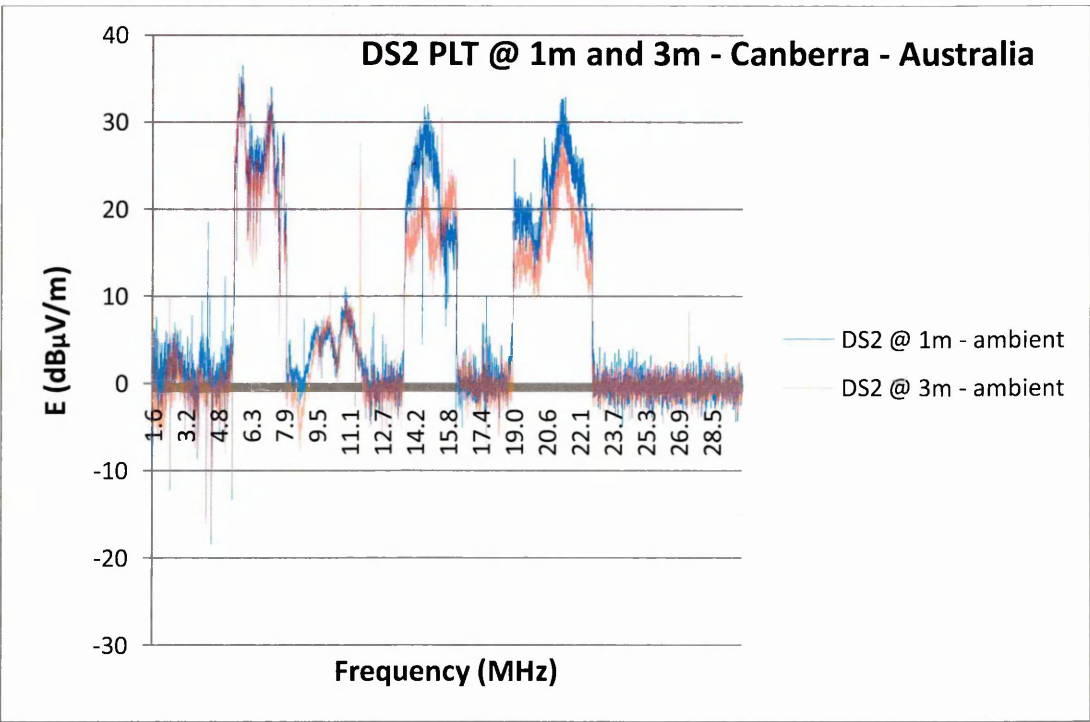


Figure 4-7 – PLT emissions Canberra, Australia (DS2)

The final area of interest is between the natural ambient noise in many locations. One could quickly make measurements in many areas and draw conclusions and, as an

example, Figure 4-8 shows the difference in ambient noise in the three locations presented in the preceding paragraphs.

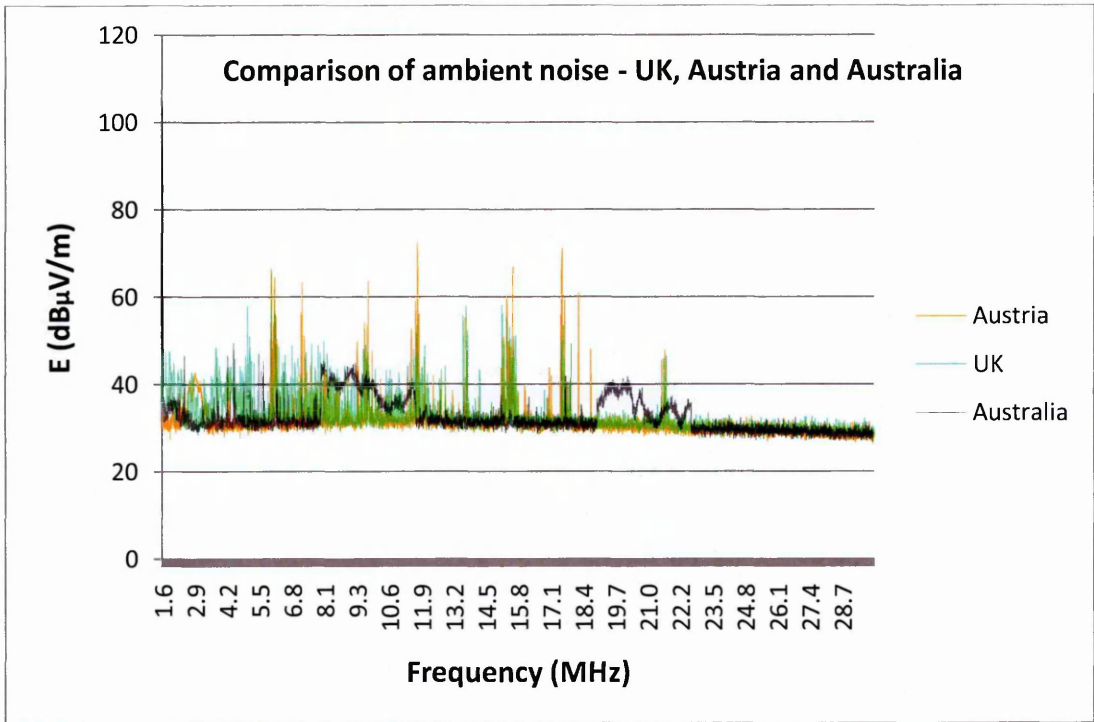


Figure 4-8 – Comparison of global rural noise

It can be seen that the Australian ambient noise is generally quieter, as one would expect from a largely dispersed country with a low population per area density, but in certain areas it increases in bands. The UK and Austria have higher impulse noise at certain frequencies, but of note is that the general lower noise floor does not drop below 30dBµV/m, which is a limitation of the measuring system (primarily the antenna) common with most CISPR 16-1 compliant equipment. Therefore if one is measuring PLT and including the ambient noise (as is the case with most research to date) one should not expect to read it across to any other location without some statement of error.

4.4.7 Results – risk adjusted (Monte-Carlo)

The results shown above are in their raw format as read from the EMC analyser and, as is best practice in accordance with CISPR 16-4, a statement of error should be made. For the ambient comparison, all measurements were made in the far-field and therefore a typical CISPR 16-1 error evaluation can be undertaken. This would lead to an expected error in the range $\pm 5\text{dB}$ to $\pm 8\text{dB}$ depending on the treatment of site factors. In the case, however, of the actual PLT measurements above, one could take a Monte-Carlo simulation to account for the improper use of the loop antenna in the near-field and the uncertainty due to ambient noise - and one would quickly conclude that an error budget as large as $\pm 15\text{dB}$ is possible. For this reason great care must be taken when attempting to apply the above figures to a prediction of likely interference to a victim receiver.

4.5 MEASUREMENT 2 – EMC ANALYSER

4.5.1 Rationale

The aim of this test was to determine the attenuation with distance of a PLT signal from a “typical” house. Other researchers have claimed a $1/r$ attenuation factor which is the expected attenuation factor in the far-field on a calibrated test site. As most PLT measurements are undertaken in the near-field one would expect a larger attenuation and therefore an over estimation of the effect of PLT on a victim receiver in the near-field.

4.5.2 Technique

The aim of the test was to simulate the radiated emissions from a PLT modem at fixed distances out toward the presumed far-field. As discussed in chapter 2, the presumption of where the near-field/far-field boundary is for PLT is not straightforward and there are also physical limitations at the measurement sites. For this measurement, 10 m was chosen as a compromise between each of the boundary

measurement standards in use at the time of the measurement (MPT 1570 at 1m and FCC 15 at 30 m).

4.5.3 Date and Location

The measurements were taken between the 6th and 21st January 2005 at Bradley Stoke, which is a densely populated suburban area 7 miles north of Bristol in the UK that for the purpose of this test can be considered urban due to the high density of housing and its proximity to the City of Bristol. The tests were conducted during week days during normal working hours. The house is a 4 bedroom detached premises built in 1987 with original wiring as shown in Figure 4-9 and Figure 4-10.



Figure 4-9 – Bradley Stoke nr Bristol, UK - site location

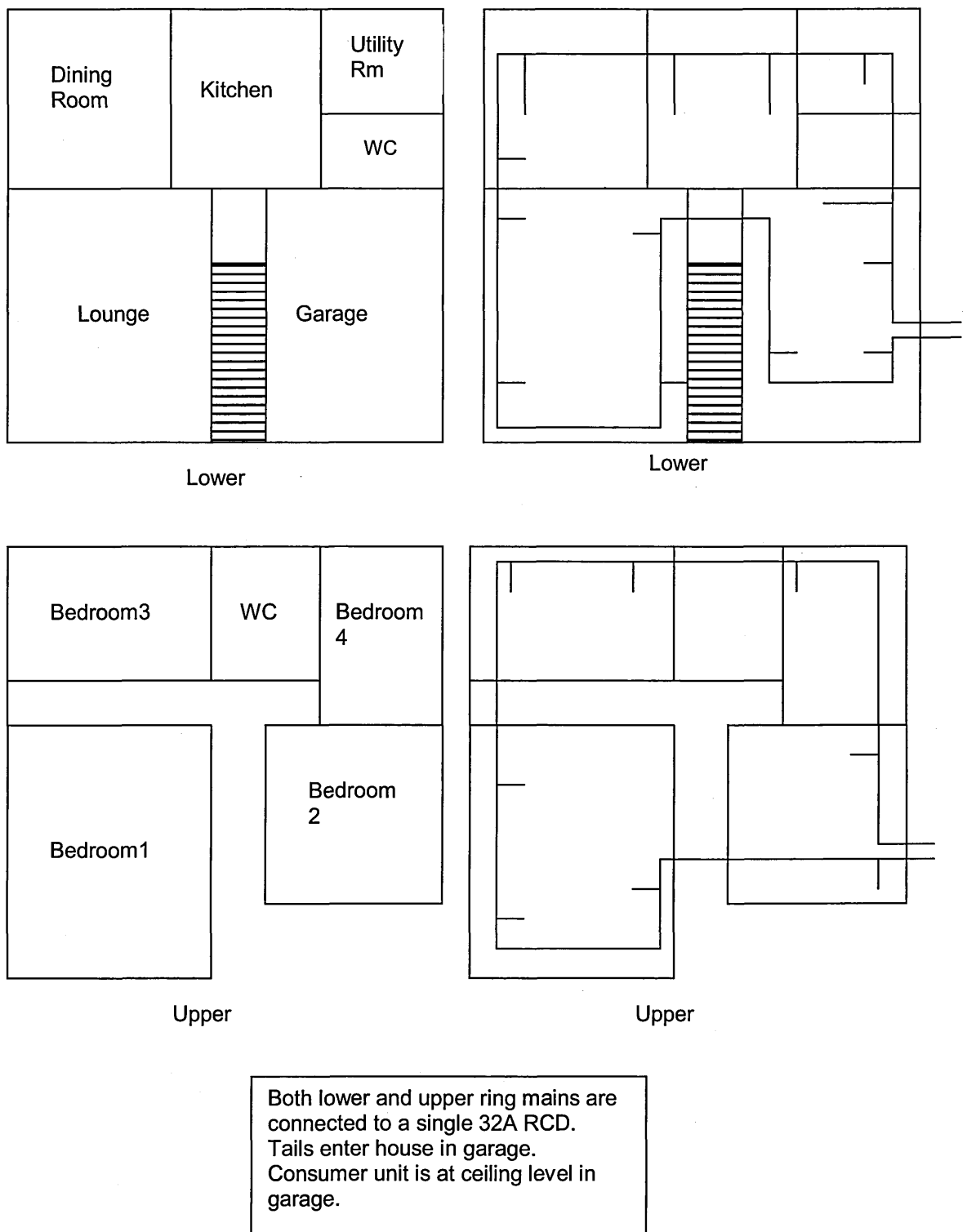


Figure 4-10 – Bradley Stoke premises electrical diagram

To simulate a modem, a Marconi 2019A signal generator was connected to the mains network as close as practical to the consumer unit using a dedicated Low Voltage (LV) signal coupler (Figure 4-11) manufactured within the PSCRG.



Figure 4-11 – PSCRG LV coupler

The function of the LV coupler is to both protect the equipment and present a matched impedance of to the power network. The estimated impedance of the mains network in the 1.6-30 MHz band is 50Ω as used by the wider research community, however the PSCRG are researching this and are due to publish findings later in 2011. Isolation from the mains voltage is provided by the two 10000pF, 1600V rated capacitors and a miniature wideband transformer. Test equipment signal port protection is provided by the diode limiter, which prevents signals greater than 1.2 V peak to peak being applied to the test equipment. This arrangement is sufficient to protect the test gear ports from short-duration high-voltage transients. The coupler is equipped with a BNC socket for connection to the test equipment and an IEC mains socket for connection to the network under test, the short lead being chosen to minimize attenuation between the coupler and the network. A circuit diagram of the coupler is shown in Figure 4-12.

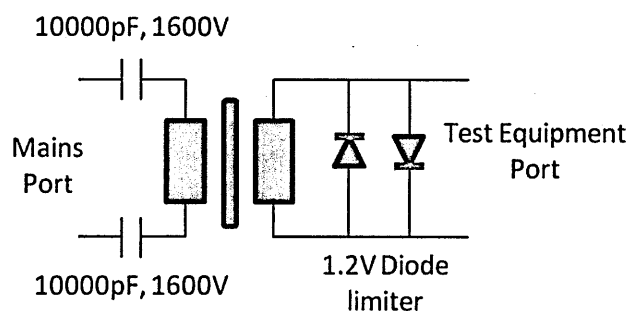


Figure 4-12 – LV coupler – circuit diagram

The PSCRG couplers were calibrated before use by connecting a pair back to back (by linking their mains ports) and performing a frequency analysis using a signal generator and the EMC receiver. In the test setup, the maximum loss across the frequency range 1.6 MHz to 30 MHz was found to be 1dB per coupler (Table 4-3). This was used as a transducer factor in the measurement file from the receiver and is therefore not included in the Monte-Carlo analysis.

Frequency (MHz)	Attenuation (dB)
1.6	0.75
2.2	0.5
5.0	0.4
12.0	0.4
16.5	0.5
30	1.0

Table 4-3 – Coupling loss of LV coupler

At the time of the experiment, typical PLT modems would output 0dBm using a 10kHz bandwidth, which equates to -40dBm/Hz where the conversion of dBm/Hz to dBm is $10\text{Log}(1.03*\text{bandwidth})$. The signal generator was set to its nominal value for the test being undertaken. The centre of the loop antenna was positioned at 0.5 m from the premises and readings were taken at 1.6MHz, 5MHz, 10MHz, 15MHz, 20Mhz, 25MHz and 30MHz for a fixed antenna height of 1.5m to the centre. These were repeated at 0.5m distances to 10m which was a limitation on the cabling available and the proximity to neighbouring houses. Figure 4-13 shows schematically the test set up.

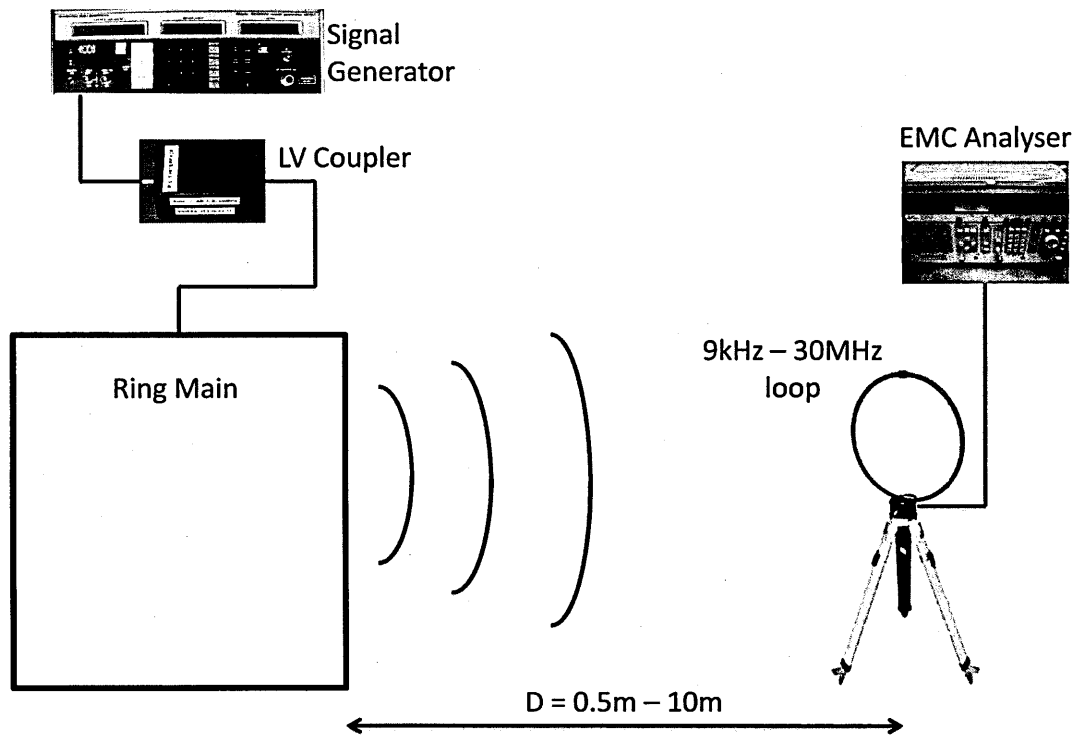


Figure 4-13 – Attenuation with distance – test setup

The measurements were repeated with different transmit powers, and also at different directions from the premises, to determine the effects of varying each parameter. No error factors were added for this test, as the aim was to observe the relative signal strength and not to draw conclusions on the actual electric field strength. As before, the EMC analyser was set to a 10kHz bandwidth and set to use the quasi-peak detector. The Antenna Factor and H to E field conversion factor were added.

It is normal in telecommunications engineering to use dBm as the measure of signal amplitude relative to 1mW as the source. In the regression test results that follow, a comparison is made of the electric field strength in Volts per metre to the injected power. To convert from dBm to V_{RMS} the following equations have been used:

$$V_{RMS} = \sqrt{P(W) * Z(\Omega)} \quad (4-2)$$

Where

$$P(W) = \frac{10^{\left(\frac{P(dBm)}{10}\right)}}{1000} \tag{4-3}$$

and Z is assumed to be 50Ω

4.5.4 Results 4 – 39dBm with antenna perpendicular

Before the regression test was undertaken, a measurement of the ambient noise was taken at 5m (mid distance) to allow a comparison to measured values later.

Frequency (MHz)	E (dBμV/m)
1.6	27.4
5	27.5
10	28.6
15	27.6
20	27.5
25	26.4
30	25.5

Table 4-4 – Ambient noise @ 5m with antenna perpendicular

A signal strength of 39dBm (20V_{RMS}) was injected into the mains network and the receiving antenna was placed perpendicular to the front of the premises at 0.5m. 39dBm was chosen as the largest signal level that the equipment could safely accommodate with the aim being to minimise the effect of ambient noise due to other intentional radiators in the vicinity by transmitting a much larger signal than would normally be expected from PLT. Table 4-5 through Table 4-11 show the measured equivalent electric field strength in dBμV/m and also the equivalent field strength in V/m (in order for the attenuation of field strength with distance to be charted in a linear format and brought to a common baseline for comparison).

Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	1.6	69.5	0.002985383
1.5	1.6	70.5	0.003349654
2	1.6	69.5	0.002985383
2.5	1.6	68.5	0.002660725
3	1.6	66.5	0.002113489
3.5	1.6	66.5	0.002113489
4	1.6	65.5	0.001883649
4.5	1.6	64.5	0.001678804
5	1.6	63.5	0.001496236
6	1.6	61.5	0.001188502
7	1.6	57.5	0.000749894
8	1.6	55.5	0.000595662
9	1.6	46.5	0.000211349
10	1.6	43.5	0.000149624

Table 4-5 – Attenuation with distance @ 1.6MHz

Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	5	73.5	0.004731513
1.5	5	73.5	0.004731513
2	5	71.5	0.003758374
2.5	5	71.5	0.003758374
3	5	68.5	0.002660725
3.5	5	67.5	0.002371374
4	5	67.5	0.002371374
4.5	5	66.5	0.002113489
5	5	65.5	0.001883649
6	5	61.5	0.001188502
7	5	64.5	0.001678804
8	5	61.5	0.001188502
9	5	67.5	0.002371374
10	5	62.5	0.001333521

Table 4-6 – Attenuation with distance @ 5MHz

Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	10	67.5	0.002371374
1.5	10	68.5	0.002660725
2	10	71.5	0.003758374
2.5	10	71.5	0.003758374
3	10	71.5	0.003758374
3.5	10	70.5	0.003349654
4	10	70.5	0.003349654
4.5	10	68.5	0.002660725
5	10	69.5	0.002985383
6	10	67.5	0.002371374
7	10	61.5	0.001188502
8	10	64.5	0.001678804
9	10	67.5	0.002371374
10	10	62.5	0.001333521

Table 4-7– Attenuation with distance @ 10MHz

Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	15	78.5	0.008413951
1.5	15	77.5	0.007498942
2	15	72.5	0.004216965
2.5	15	73.5	0.004731513
3	15	75.5	0.005956621
3.5	15	75.5	0.005956621
4	15	75.5	0.005956621
4.5	15	74.5	0.005308844
5	15	75.5	0.005956621
6	15	75.5	0.005956621
7	15	69.5	0.002985383
8	15	74.5	0.005308844
9	15	81.5	0.011885022
10	15	76.5	0.006683439

Table 4-8 – Attenuation with distance @ 15MHz

Distance (m)	Frequency (MHz)	E (dB μ V/m)	E (V/m)
1	20	78.5	0.008413951
1.5	20	77.5	0.007498942
2	20	82.5	0.013335214
2.5	20	82.5	0.013335214
3	20	83.5	0.014962357
3.5	20	84.5	0.01678804
4	20	85.5	0.018836491
4.5	20	84.5	0.01678804
5	20	84.5	0.01678804
6	20	84.5	0.01678804
7	20	77.5	0.007498942
8	20	81.5	0.011885022
9	20	76.5	0.006683439
10	20	72.5	0.004216965

Table 4-9 – Attenuation with distance @ 20MHz

Distance (m)	Frequency (MHz)	E (dB μ V/m)	E (V/m)
1	25	74.5	0.005308844
1.5	25	74.5	0.005308844
2	25	69.5	0.002985383
2.5	25	66.5	0.002113489
3	25	63.5	0.001496236
3.5	25	63.5	0.001496236
4	25	65.5	0.001883649
4.5	25	66.5	0.002113489
5	25	68.5	0.002660725
6	25	67.5	0.002371374
7	25	69.5	0.002985383
8	25	71.5	0.003758374
9	25	67.5	0.002371374
10	25	63.5	0.001496236

Table 4-10 – Attenuation with distance @ 25MHz

Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	30	66.5	0.002113489
1.5	30	68.5	0.002660725
2	30	67.5	0.002371374
2.5	30	65.5	0.001883649
3	30	66.5	0.002113489
3.5	30	66.5	0.002113489
4	30	66.5	0.002113489
4.5	30	69.5	0.002985383
5	30	70.5	0.003349654
6	30	69.5	0.002985383
7	30	63.5	0.001496236
8	30	69.5	0.002985383
9	30	66.5	0.002113489
10	30	63.5	0.001496236

Table 4-11 – Attenuation with distance @ 30MHz

The associated graphs for these tables are shown at Figure 4-14 to Figure 4-20. Note that the ambient noise has been subtracted to show the correct representation of the field being measured.

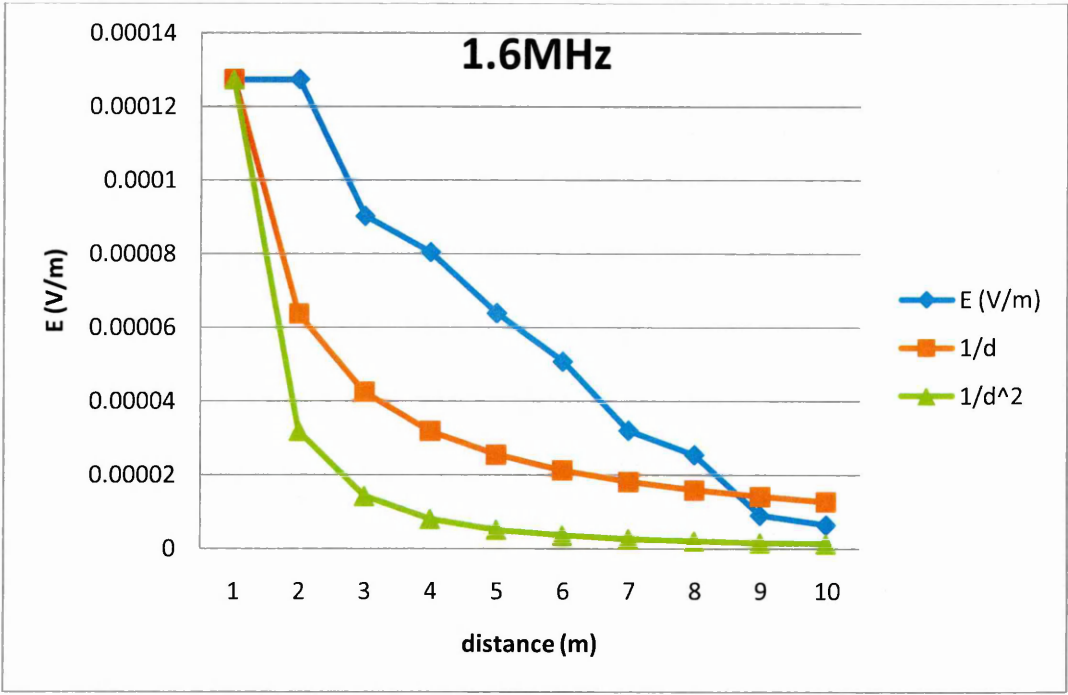


Figure 4-14 – Attenuation with distance @ 1.6MHz

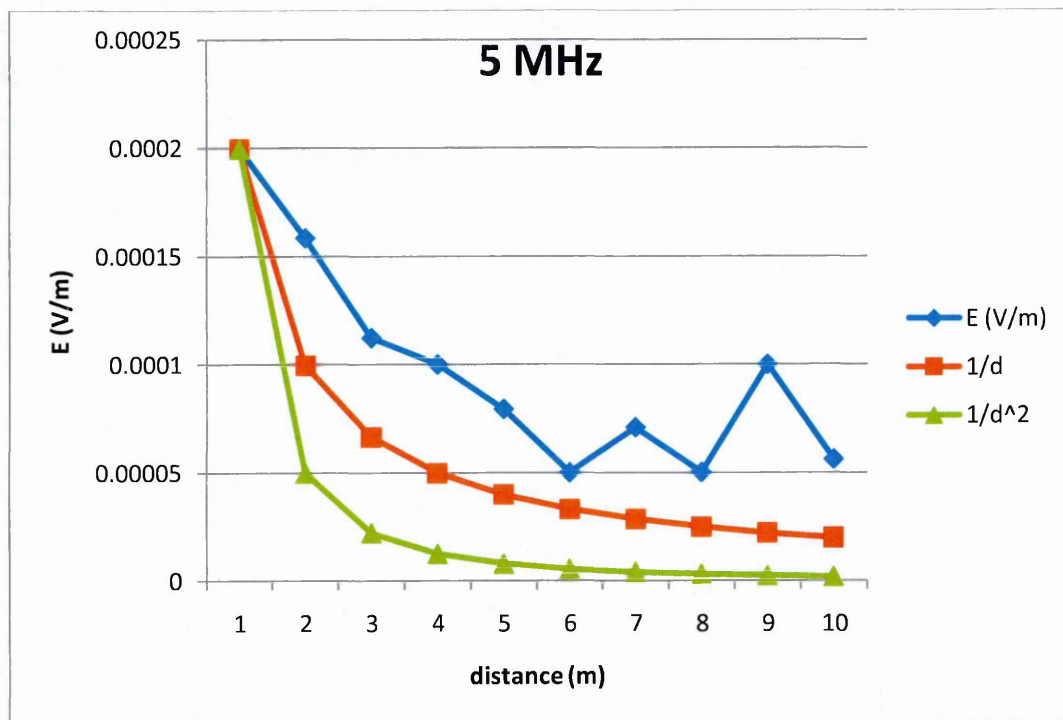


Figure 4-15 – Attenuation with distance @ 5MHz

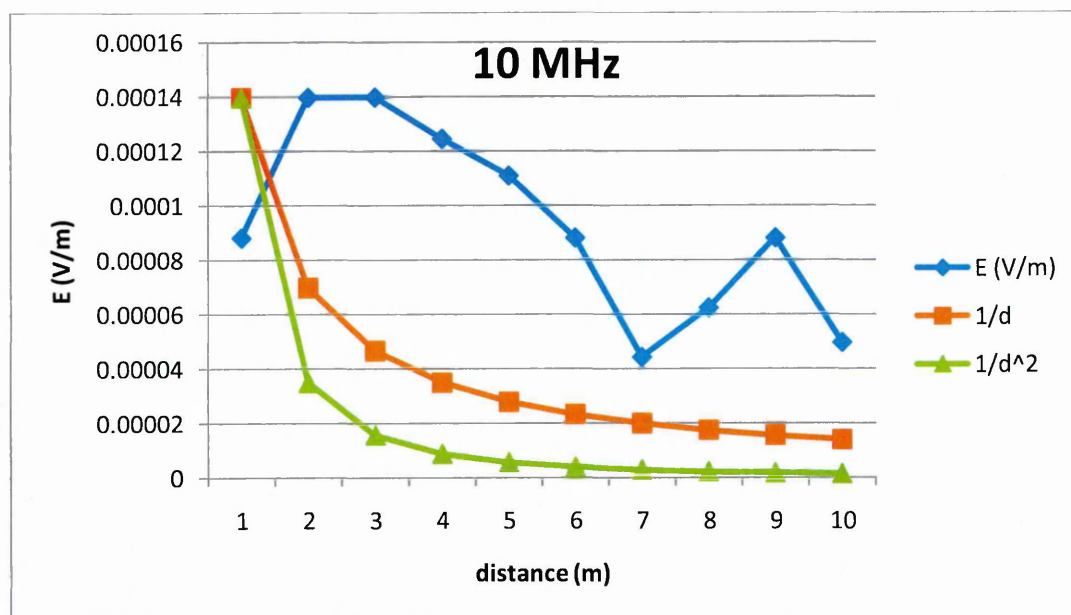


Figure 4-16 – Attenuation with distance @ 10MHz

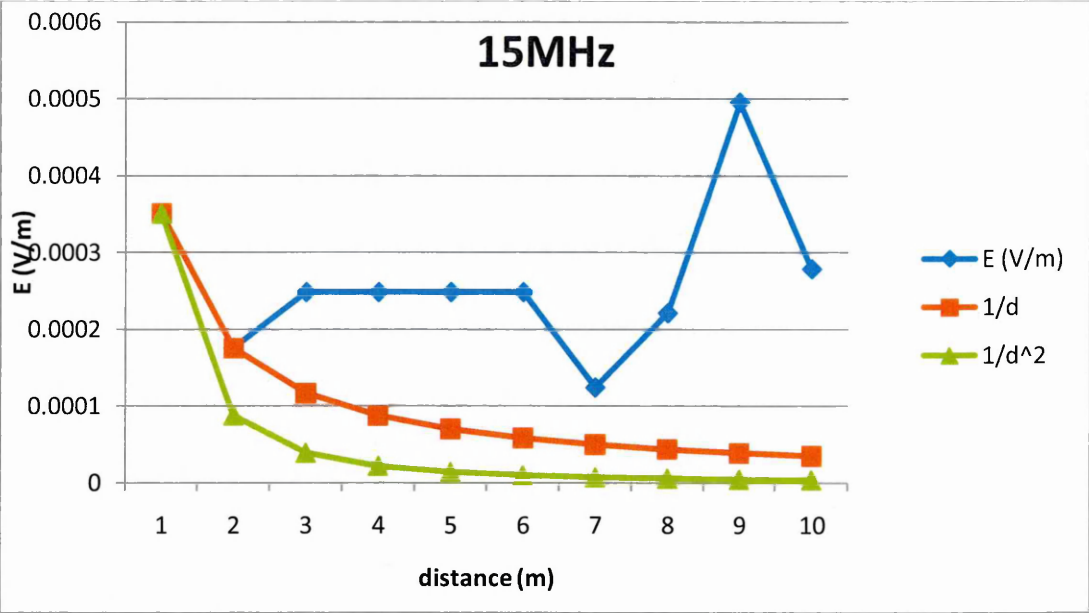


Figure 4-17 – Attenuation with distance @ 15MHz

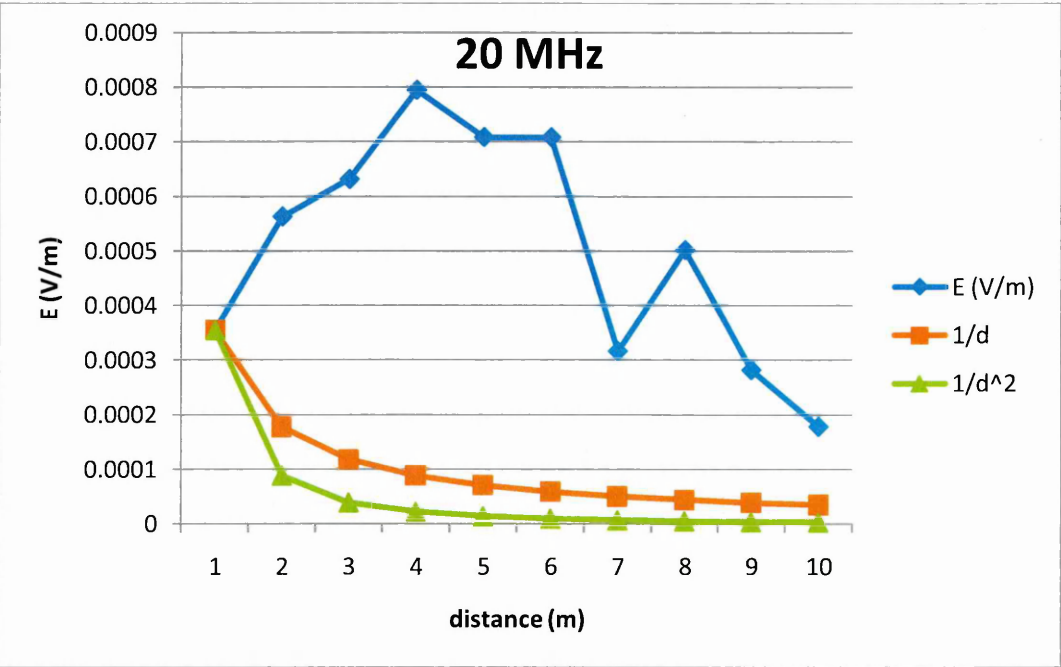


Figure 4-18 – Attenuation with distance @ 20MHz

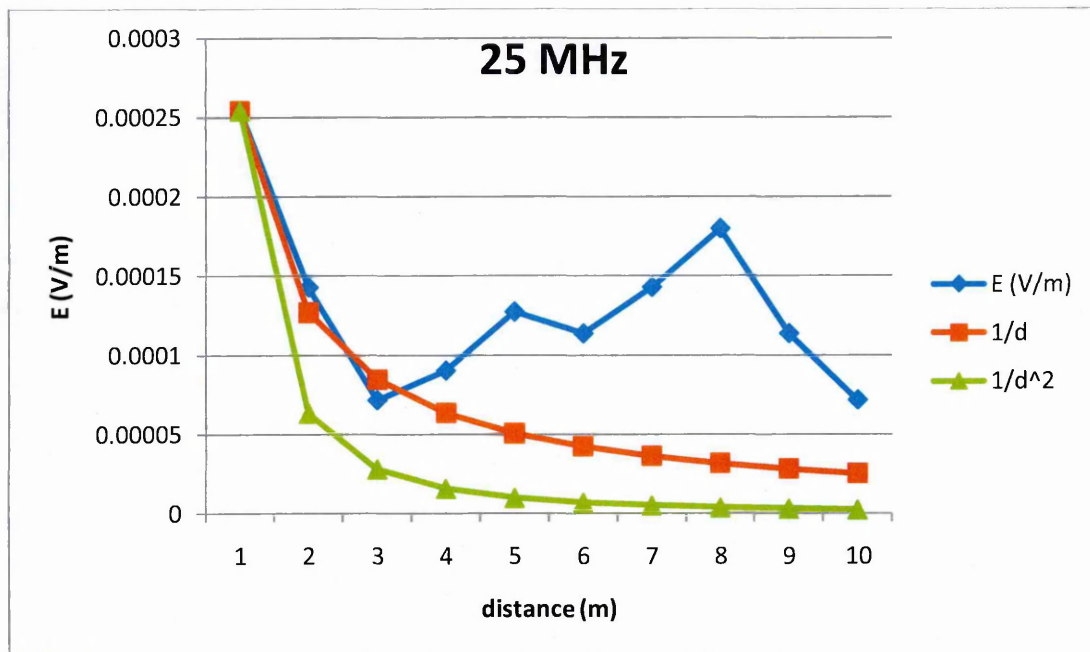


Figure 4-19 – Attenuation with distance @ 25MHz

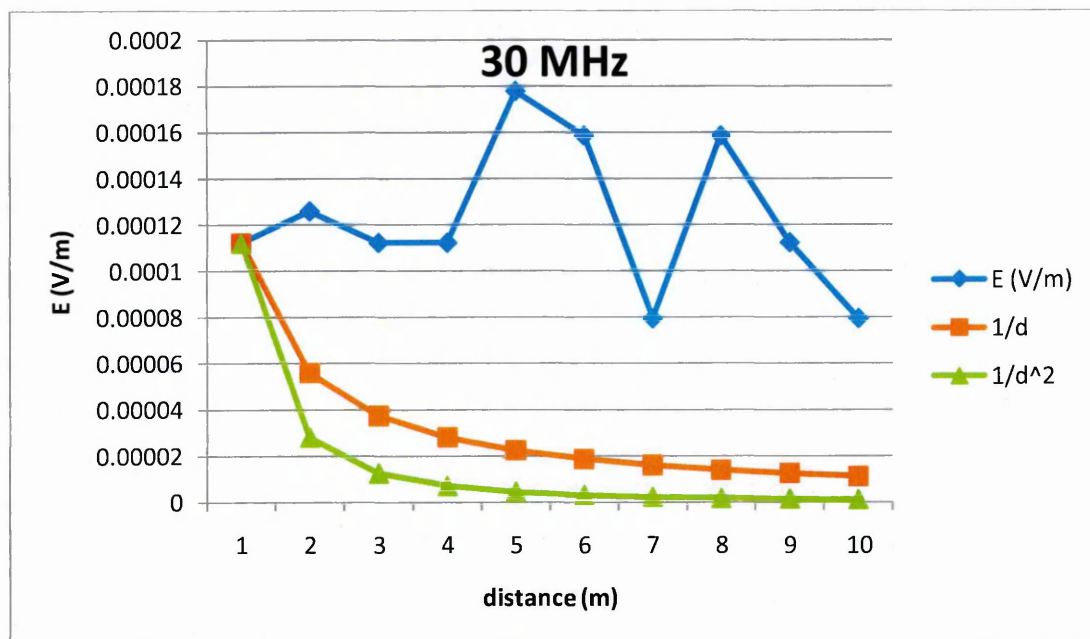


Figure 4-20 – Attenuation with distance @ 30MHz

From the graphs above it can be seen that the attenuation with distance for a perpendicular loop antenna, which is the orientation that a typical radiated emission test would take, does not follow a $1/r$ roll off. At lower frequencies it tends towards a linear roll off and at higher frequencies the signal strength actually increases. The concept in EMC measurements that a radiated field would not decrease with distance

is counter intuitive but it should be remembered that these measurements were taken in a densely populated housing area as opposed to a well calibrated OATS. As the ambient noise was subtracted from the measured values, the usual spikes that are caused by intentional radiators can be discounted. The most likely effects are associated with near-field/far-field properties, geometric effects of the premises under test and re-radiation from other premises. It is worth considering these in more detail as they are not routinely measured in any other PLT studies.

Firstly, looking at each graph in more detail shows that at 1.6 MHz and 5 MHz the roll off with distance approaches a linear regression. In free space, one would expect the roll off to be squared and approaching cubed but this is not the case here. One of the greatest factors is probably associated with the calibration data for the antenna. The Antenna Factor includes a conversion of 51.5dB to convert the measured H field to a voltage at the terminals of the EMC analyser. At low frequencies, as was mentioned in chapter 3, this is inaccurate and cannot be quantified when used in-situ. One must note it as a potential error, and further note that the effects become less as the frequency and the distance increase. The second factor is that the premises under test was a two storey building that had mains networks on both levels and in the attic. As the measurement height is the standard 1.5m at distances close to the premises, the downstairs ring main and lighting circuits are the predominant radiators from the perspective of antenna orientation. As the antenna is moved away from the downstairs ring main the roll off would expect to approach something like $1/r$, however the contribution from the upstairs ring mains increases and the observed effect is a roll off less than expected. The third and final factor has observable effects as the distance increases. From Figure 4-21 it can be seen that the premises under test is collocated with other premises in a cul-de-sac formation.



Figure 4-21 – Location of antenna during attenuation with distance test

The measurement antenna was moved from the premises along the red line indicated towards the 10m measurement point indicated by the ☆. At the 10m measuring point it can be seen that there are houses exactly opposite and a neighbouring property that contribute to the radiated field. No assessment was made as to which phases each premises were on but in any case there is limited isolation from the surrounding mains network and therefore one must assume that the injected signal is transmitted either in full or in part to the neighbouring properties. As expected the effects are more noticeable at the higher frequencies as the near-field/far-field boundary is approached and therefore the radiated field rather than the reactive field has dominance. The floor area of each house is approximately 60m^2 and therefore the ring main dimensions come into resonance from above 5MHz and at higher frequencies if one assumes that appliances attached to the mains network act as inductive loads and reduce the resonant frequency. Looking at Figure 4-17 and Figure 4-20 (15MHz – 30MHz), there are two obvious inductive peaks - which are probably standing waves caused by

constructive interference from the radiated effects of neighbouring premises. To determine the effects, the tests were repeated for antenna orientations and test points as discussed in the following paragraphs.

4.5.5 Results 5 – 39dBm with antenna parallel

The test above was repeated with the antenna oriented parallel to the premises under test. At this orientation the loop presents a null to the radiated field and for an infinitesimally small loop source placed in front of the measurement loop would cause no (or a limited) induced field. In this case there are contributions from other parts of the premises and also from adjoining premises. The individual results and their associated graphs can be found at Appendix A, but the first point of note is that each attenuation graph has less standing wave patterns than the perpendicular equivalent. The graphs for 5 MHz and 25 MHz are shown below as a demonstration of this, but it should be noted that standing waves do exist at some of the intermediate frequencies.

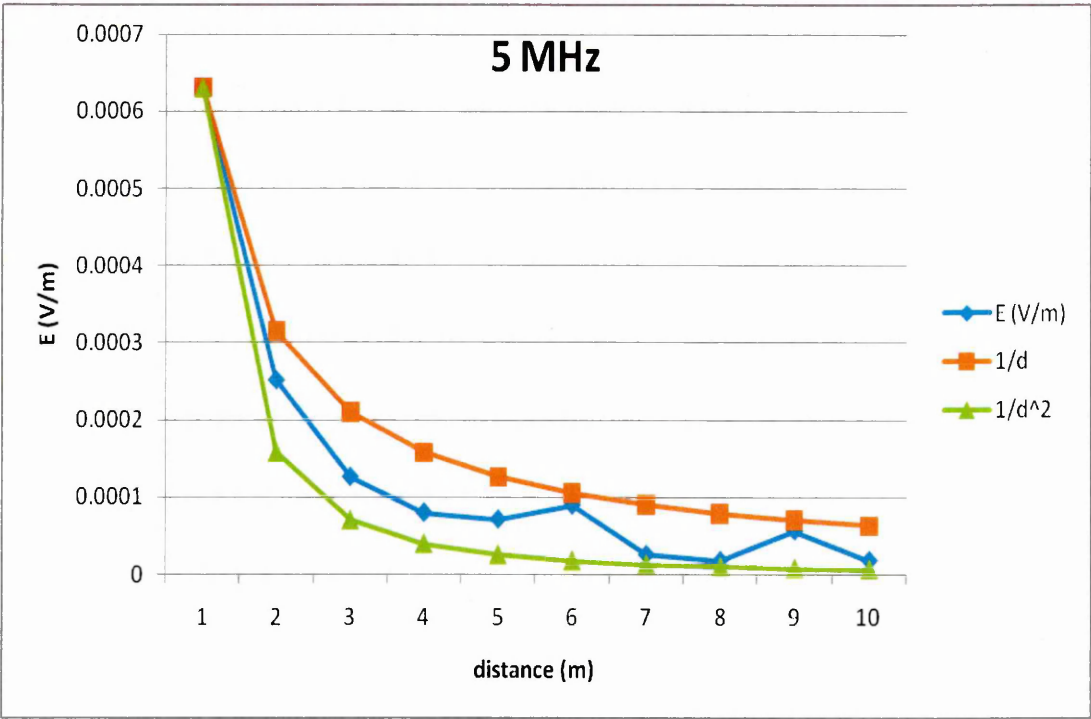


Figure 4-22 – Antenna parallel @ 5MHz

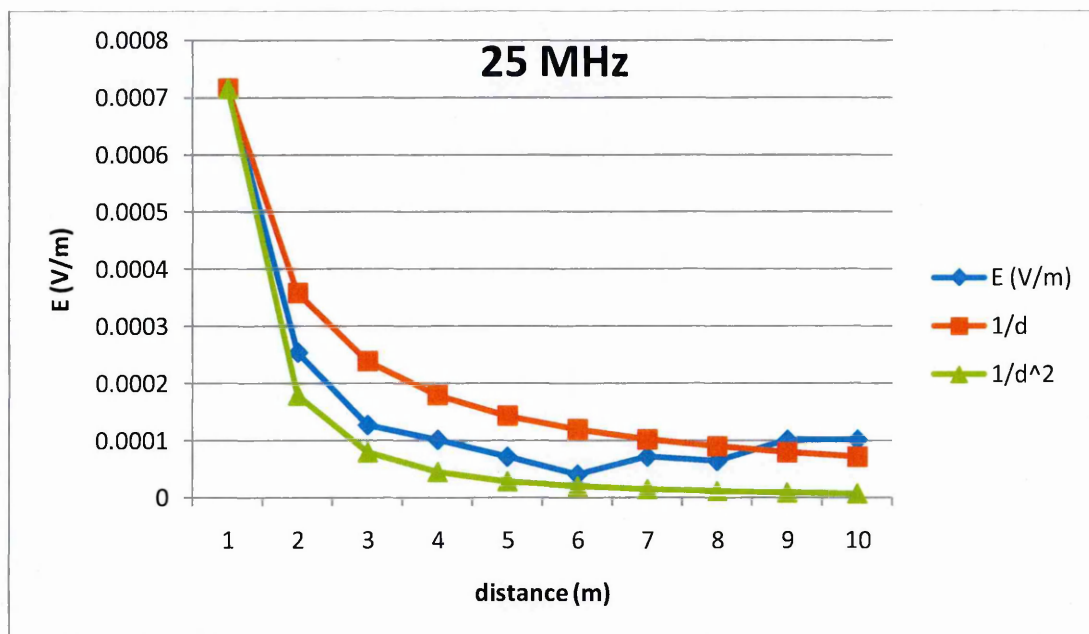


Figure 4-23 – Antenna parallel @ 25MHz

Another point to note is that the attenuation curves for these frequencies fall between a $1/r$ and $1/r^2$ attenuation pattern. It is expected that this is the case because the main contributors previously were deemed to be from a combination of standing waves from the premises under test with those from surrounding premises. With the antenna placed parallel to the house under test, the main areas of emitted radiation are discounted from the readings because the antenna presents a null to that contribution. What is actually being measured here, then, is predominantly other surrounding houses and a contribution from the extremities of the premises under test. In this case the readings are more likely to be in the far-field than the near-field and therefore the attenuation graphs correlate more closely to the theoretical prediction.

4.5.6 Results 6 – 39dBm vector sum of results 4 and results 5

Having collected the underlying data with the antenna in both the perpendicular and parallel orientations, it was decided to add the vector some of the contributions as this would more accurately reflect the radiated emission at that point in space. Best EMC practice recognises that to take measurements in the near-field requires a multi axis approach with the most realistic value being a vector sum of three axes. For example

the CISPR 15 test for lighting equipment states that the equipment should be placed within the confines of a Large Loop Antenna (LLA), which is a three axis loop antenna for use at low frequencies. The PSCRG existing tripod only has a two axis orientation and therefore the horizontal axis could not be measured. Other researchers have undertaken two axis measurements before by rotating the antenna to measure the maximum field at each position but this is time consuming and requires the individual to walk into the measured field. It was therefore considered that a vectorially added two axis measurement offered the best compromise.

Appendix B shows the attenuation with distance graphs for the vector sum of the perpendicular and parallel contributions. By observation one can see that the graphs for each frequency now all follow the shape of a $1/r$ curve but that each has a slightly different gradient. This makes sense because the measured value at each distance now takes account of the contribution of all houses in the vicinity and neither the near or far-field effects dominate. By applying a trend line using a power series (which offers the best fit) it can be determined that the attenuation with distance is between $1/r^2$ and $1/\sqrt{r}$ which is more typical. $1/r^2$ is typical of near-field regression and $1/\sqrt{r}$ would be expected when local reflections from the earth or obstacles cause a regression which is above $1/r$ but still falls off in a predictable manner.

4.5.7 Results 7 – -7dBm with antenna perpendicular

The tests above were repeated for a reduced signal strength of 100mV (-7dBm) to determine the effects on measured results when the signal strength approaches the ambient noise floor. The associated tables and graphs are shown at Appendix C. It is difficult to draw a firm conclusion from the graphs because the measurements were taken on different days and although the ambient noise was collected each day, the change in network loading was not determined. In hindsight, measurements for all orientations should have been collected, but due to the manual nature of these tests,

the duration to complete them increases as more permutations are considered. At the lower frequency end of the spectrum, the roll-off features look broadly similar and this is possibly because at these frequencies the field is primarily reactive and therefore the effects in network impedance do not manifest themselves in the same way as they do for the radiated field.

Conclusions from these results will be discussed in Chapter 5, however the following is worthy of note here. H antenna orientation is significant. At distances less than 3m, (certainly in the near-field) an antenna position parallel to the house gives a reading up to 10dBuV/m higher. As one moves into the far-field the loop positioned at 90 degrees gives a higher reading of the same order of magnitude. This is interesting because most compliance proposals require a loop at 90 degrees at 1m or 3m which does not necessarily give the highest reading.

4.6 MEASUREMENT 3 – DIFFERENCE BETWEEN E AND H

4.6.1 Rationale

Early PLT literature assumed that the signal to be measured would be small in comparison with other EMC measurements and that specialist equipment such as the University of Hertfordshire tuneable antennas would be required. It was perceived by early researchers that using a traditional electric field measuring antenna such as a monopole antenna for EMC radiated emission compliance measurements would provide inaccurate results. In the test above, however, the injection voltage of 20V_{RMS} was expected to be detectable and therefore the effects of measuring the electric field directly could be compared with deriving it from a magnetic field measurement. Some Military EMC tests measure the electric and magnetic field independently to determine more accurately the fields from communication equipment.

4.6.2 Technique

The same technique as described in Figure 4-13 was used except that the Schaffner Loop was replaced by an active 1m monopole that required no correction for antenna factor.

4.6.3 Results 8 – 39dBm with monopole antenna

The results of the regression testing of a 39dBm simulated PLT signal using a monopole antenna are detailed Appendix D. The regression curves follow a typical $1/r$ shape and, as predicted, approaches $1/r^2$ at lower frequencies and has a more gradual roll-off towards $1/\sqrt{r}$ at higher frequencies. As the radiated field components become significant, then reflections and contributions from neighbouring properties again cause standing wave patterns. Although not documented here, the tests were repeated with a -7dBm input and the monopole performed as expected at distances close to the premises but not so well beyond 5m due to its lack of sensitivity. From the initial results the use of monopoles for measurement distances closer than 3m show an unexpected performance which is superior to a single orientation loop measurement. Further work would have to be undertaken to determine a more accurate correlation.

The key conclusion to be drawn from these results is the difference in measured values of the radiated field when using a loop antenna or a monopole antenna. With an injected signal of 39dBm, which causes a radiation of 50dB μ V/m - 60dB μ V/m above the ambient background noise, the errors that would normally be apparent are greatly reduced. There is nonetheless a very significant difference between the field as measured by the monopole, compared to a loop in the traditional compliance orientation (perpendicular) and compared to the vector sum as discussed earlier. Table 4-12 to Table 4-18 demonstrate this difference by frequency and antenna orientation.

Dist (m)	Freq (MHz)	Monopole (dBμV/m)	Loop parallel (dBμV/m)	Loop perp (dBμV/m)	Loop Vector (dBμV/m)	E-H parallel (dBμV/m)	E-H perp (dBμV/m)	E-H Vector (dBμV/m)
1	1.6	90	69.5	69.5	72.5	20.5	20.5	17.5
2	1.6	83	72.5	69.5	74.3	10.5	13.5	8.7
3	1.6	77	67.5	66.5	70.0	9.5	10.5	7.0
4	1.6	74	65.5	65.5	68.5	8.5	8.5	5.5
5	1.6	70	64.5	63.5	67.0	5.5	6.5	3.0
6	1.6	70	63.5	61.5	65.6	6.5	8.5	4.4
7	1.6	56	62.5	57.5	63.7	-6.5	-1.5	-7.7
8	1.6	48	60.5	55.5	61.7	-12.5	-7.5	-13.7
9	1.6	42	60.5	46.5	60.7	-18.5	-4.5	-18.7
10	1.6	73	54.5	43.5	54.8	18.5	29.5	18.2

Table 4-12 – Comparison of directly measured E to derived E @ 1.6MHz

Dist (m)	Freq (MHz)	Monopole (dBμV/m)	Loop parallel (dBμV/m)	Loop perp (dBμV/m)	Loop Vector (dBμV/m)	E-H parallel (dBμV/m)	E-H perp (dBμV/m)	E-H Vector (dBμV/m)
1	5	89	83.5	73.5	83.9	5.5	15.5	5.1
2	5	83	75.5	71.5	77.0	7.5	11.5	6.0
3	5	79	69.5	68.5	72.0	9.5	10.5	7.0
4	5	77	65.5	67.5	69.6	11.5	9.5	7.4
5	5	72	64.5	65.5	68.0	7.5	6.5	4.0
6	5	73	66.5	61.5	67.7	6.5	11.5	5.3
7	5	71	55.5	64.5	65.0	15.5	6.5	6.0
8	5	73	52.5	61.5	62.0	20.5	11.5	11.0
9	5	73	62.5	67.5	68.7	10.5	5.5	4.3
10	5	71	52.5	62.5	62.9	18.5	8.5	8.1

Table 4-13 – Comparison of directly measured E to derived E @ 5MHz

Dist (m)	Freq (MHz)	Monopole (dBμV/m)	Loop parallel (dBμV/m)	Loop perp (dBμV/m)	Loop Vector (dBμV/m)	E-H parallel (dBμV/m)	E-H perp (dBμV/m)	E-H Vector (dBμV/m)
1	10	81	73.5	67.5	74.5	7.5	13.5	6.5
2	10	76	71.5	71.5	74.5	4.5	4.5	1.5
3	10	75	69.5	71.5	73.6	5.5	3.5	1.4
4	10	75	64.5	70.5	71.5	10.5	4.5	3.5
5	10	74	62.5	69.5	70.3	11.5	4.5	3.7
6	10	76	60.5	67.5	68.3	15.5	8.5	7.7
7	10	76	51.5	61.5	61.9	24.5	14.5	14.1
8	10	75	54.5	64.5	64.9	20.5	10.5	10.1
9	10	75	62.5	67.5	68.7	12.5	7.5	6.3
10	10	69	59.5	62.5	64.3	9.5	6.5	4.7

Table 4-14 – Comparison of directly measured E to derived E @ 10MHz

Dist (m)	Freq (MHz)	Monopole (dB μ V/m)	Loop parallel (dB μ V/m)	Loop perp (dB μ V/m)	Loop Vector (dB μ V/m)	E-H parallel (dB μ V/m)	E-H perp (dB μ V/m)	E-H Vector (dB μ V/m)
1	15	94	72.5	78.5	79.5	21.5	15.5	14.5
2	15	91	67.5	72.5	73.7	23.5	18.5	17.3
3	15	90	68.5	75.5	76.3	21.5	14.5	13.7
4	15	89	61.5	75.5	75.7	27.5	13.5	13.3
5	15	88	57.5	75.5	75.6	30.5	12.5	12.4
6	15	87	55.5	75.5	75.5	31.5	11.5	11.5
7	15	86	62.5	69.5	70.3	23.5	16.5	15.7
8	15	86	60.5	74.5	74.7	25.5	11.5	11.3
9	15	85	72.5	81.5	72.5	12.5	3.5	12.5
10	15	87	65.5	76.5	76.8	21.5	10.5	10.2

Table 4-15 – Comparison of directly measured E to derived E @ 15MHz

Dist (m)	Freq (MHz)	Monopole (dB μ V/m)	Loop parallel (dB μ V/m)	Loop perp (dB μ V/m)	Loop Vector (dB μ V/m)	E-H parallel (dB μ V/m)	E-H perp (dB μ V/m)	E-H Vector (dB μ V/m)
1	20	101	87.5	78.5	88.0	13.5	22.5	13.0
2	20	98	84.5	82.5	86.6	13.5	15.5	11.4
3	20	97	82.5	83.5	86.0	14.5	13.5	11.0
4	20	96	80.5	85.5	86.7	15.5	10.5	9.3
5	20	96	79.5	84.5	85.7	16.5	11.5	10.3
6	20	94	78.5	84.5	85.5	15.5	9.5	8.5
7	20	93	79.5	77.5	81.6	13.5	15.5	11.4
8	20	90	76.5	81.5	82.7	13.5	8.5	7.3
9	20	87	73.5	76.5	78.3	13.5	10.5	8.7
10	20	88	57.5	72.5	72.6	30.5	15.5	15.4

Table 4-16 – Comparison of directly measured E to derived E @ 20MHz

Dist (m)	Freq (MHz)	Monopole (dB μ V/m)	Loop parallel (dB μ V/m)	Loop perp (dB μ V/m)	Loop Vector (dB μ V/m)	E-H parallel (dB μ V/m)	E-H perp (dB μ V/m)	E-H Vector (dB μ V/m)
1	25	101	82.5	74.5	83.1	18.5	26.5	17.9
2	25	98	73.5	69.5	75.0	24.5	28.5	23.0
3	25	98	67.5	63.5	69.0	30.5	34.5	29.0
4	25	95	65.5	65.5	68.5	29.5	29.5	26.5
5	25	94	62.5	68.5	69.5	31.5	25.5	24.5
6	25	96	57.5	67.5	67.9	38.5	28.5	28.1
7	25	95	62.5	69.5	70.3	32.5	25.5	24.7
8	25	93	61.5	71.5	71.9	31.5	21.5	21.1
9	25	93	65.5	67.5	69.6	27.5	25.5	23.4
10	25	94	65.5	63.5	67.6	28.5	30.5	26.4

Table 4-17 – Comparison of directly measured E to derived E @ 25MHz

Dist (m)	Freq (MHz)	Monopole (dBµV/m)	Loop parallel (dBµV/m)	Loop perp (dBµV/m)	Loop Vector (dBµV/m)	E-H parallel (dBµV/m)	E-H perp (dBµV/m)	E-H Vector (dBµV/m)
1	30	90	73.5	66.5	74.3	16.5	23.5	15.7
2	30	88	73.5	67.5	74.5	14.5	20.5	13.5
3	30	87	70.5	66.5	72.0	16.5	20.5	15.0
4	30	84	66.5	66.5	69.5	17.5	17.5	14.5
5	30	83	66.5	70.5	72.0	16.5	12.5	11.0
6	30	84	64.5	69.5	70.7	19.5	14.5	13.3
7	30	83	60.5	63.5	65.3	22.5	19.5	17.7
8	30	80	59.5	69.5	69.9	20.5	10.5	10.1
9	30	79	61.5	66.5	67.7	17.5	12.5	11.3
10	30	78	72.5	63.5	73.0	5.5	14.5	5.0

Table 4-18 – Comparison of directly measured E to derived E @ 30MHz

The columns titled E-H are the difference in electric field strength of the directly measured electric field of the monopole (E) compared to the electric field that has been derived from the magnetic field (H). It can be seen that there is significant variation in the field measurements with the H derived field under reading by 29 dBµV/m (25 MHz @ 3m) and over reading by 18 dBµV/m (1.6MHz @ 9m). Without further measurement on a calibrated OATS it is not possible to determine the cause of the error. The purpose of these tests was to clarify the errors mentioned in chapter 3 regarding the derived electric field and how it can be used in an open test site but not in the near-field of a complex structure with any degree of accuracy.

4.6.4 Results 9 – attenuation from real PLT modem

During the same measurement timeframe, the PSCRG were provided with a pair of Main.net PLUS (Power Line Ultimate System) modems. Main.net provide a range of modem types for access, in-house and control applications, with each type having a different modulation scheme tailored to the application. The modems used for this test were the Main.net PLUS in-house variant. The aim of the test was to confirm that the attenuation with distance observed in the previous test could be read across to actual PLT modems. At the time of the test there was competition in the market place and Main.net did not provide specification information for public consumption, although it is

now believed that a frequency hopping spread spectrum was used as the modulation scheme.

The test layout was the same as in Figure 4-13 (Schaffner loop) with the signal generator replaced by the PLT modems. The first test, was to compare the PLT output to that of the ambient noise for the purpose of identifying frequencies with a large signal to noise ratio. These would then be used as spot frequencies during attenuation testing. With the antenna placed at 5m, a sweep of the ambient noise was taken in both the perpendicular and parallel orientations. With the PLT modems connected, a large file transfer between two laptops was set up with a transfer rate of 200kb/s and the measurement at 5m repeated for both perpendicular and parallel orientations. Figure 4-24 shows the comparison of Main.net PLT to ambient at 5m with the measured value being the vector sum of measurements with the loop in both perpendicular and parallel orientations.

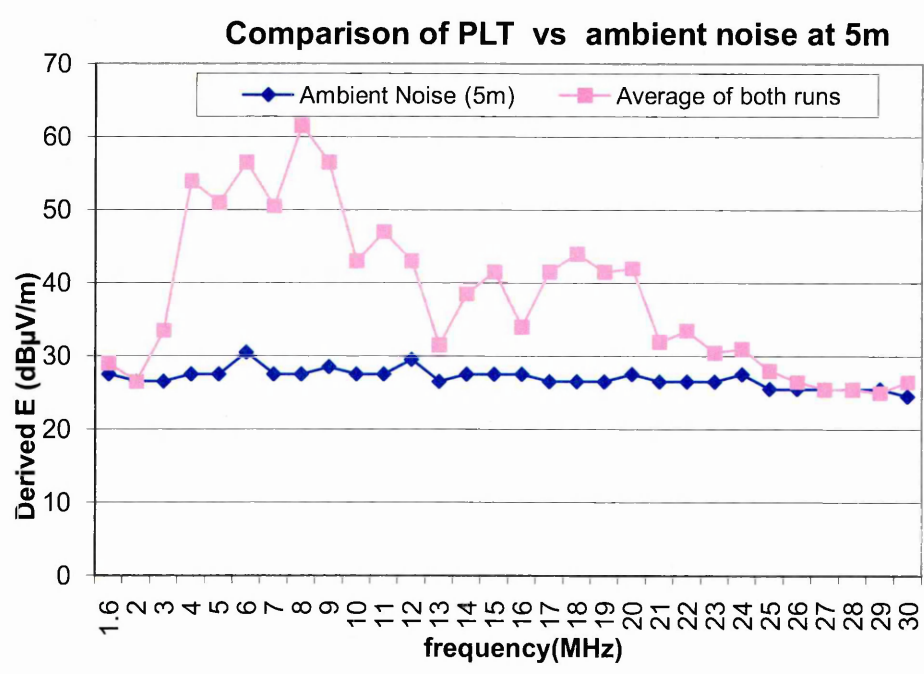


Figure 4-24 – Comparison of PLT to ambient noise

The readings confirmed the literature by both the BBC and OfCom that noted that the spectrum was spread across a large portion of the HF band and the measured values

were similar to those taken in other Main.net trial areas. From the graph it was decided to use the portion from 3.5 MHz – 17 MHz to undertake regression measurements, as these had the highest signal to noise ratio. Figure 4-25 to Figure 4-29 show the attenuation with distance of the PLT signal taken as the vector sum of perpendicular and parallel orientations of the measuring loop antenna with the ambient noise subtracted.

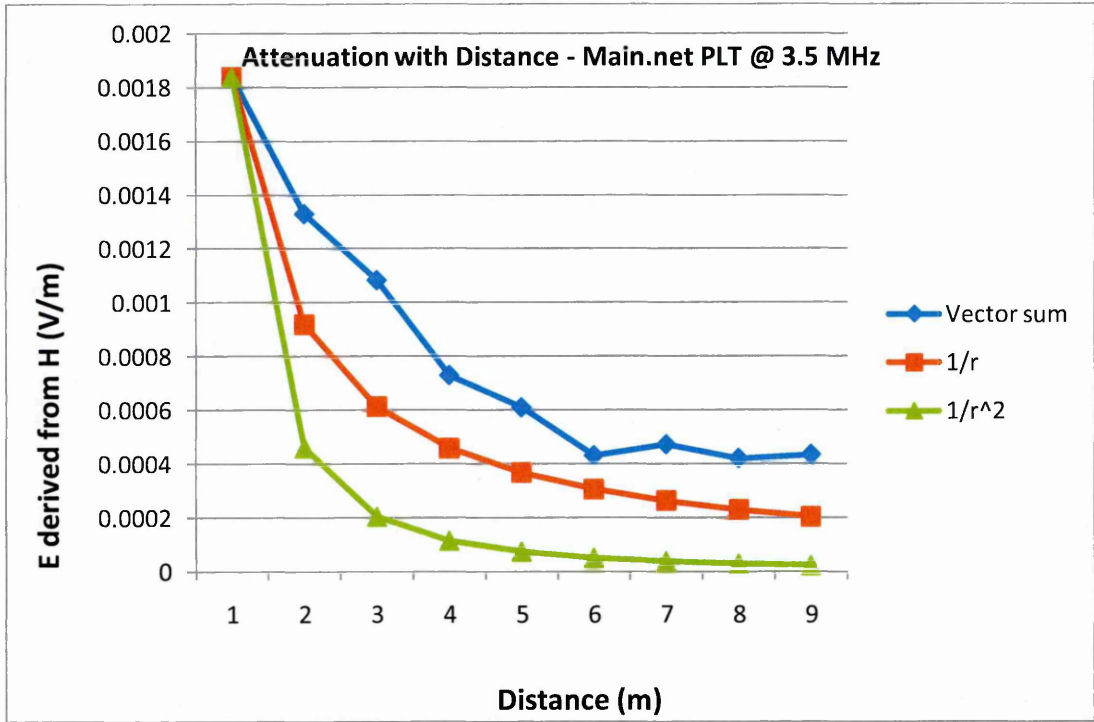


Figure 4-25 – Attenuation with distance of Main.net PLT @ 3.5Mhz

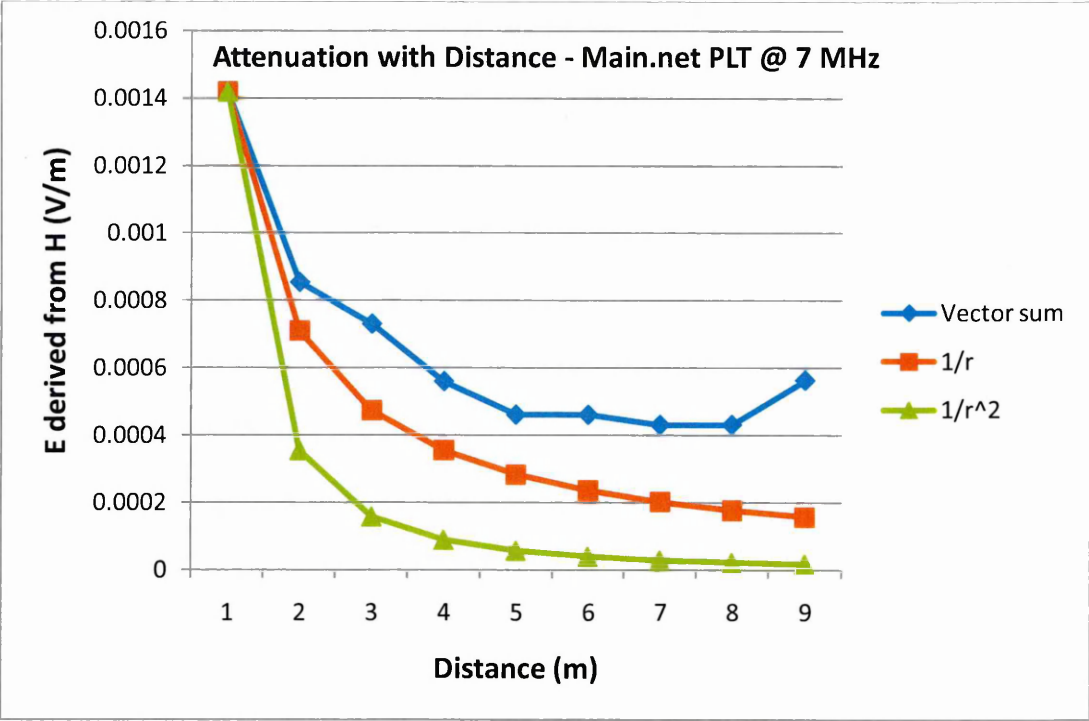


Figure 4-26 – Attenuation with distance of Main.net PLT @ 7Mhz

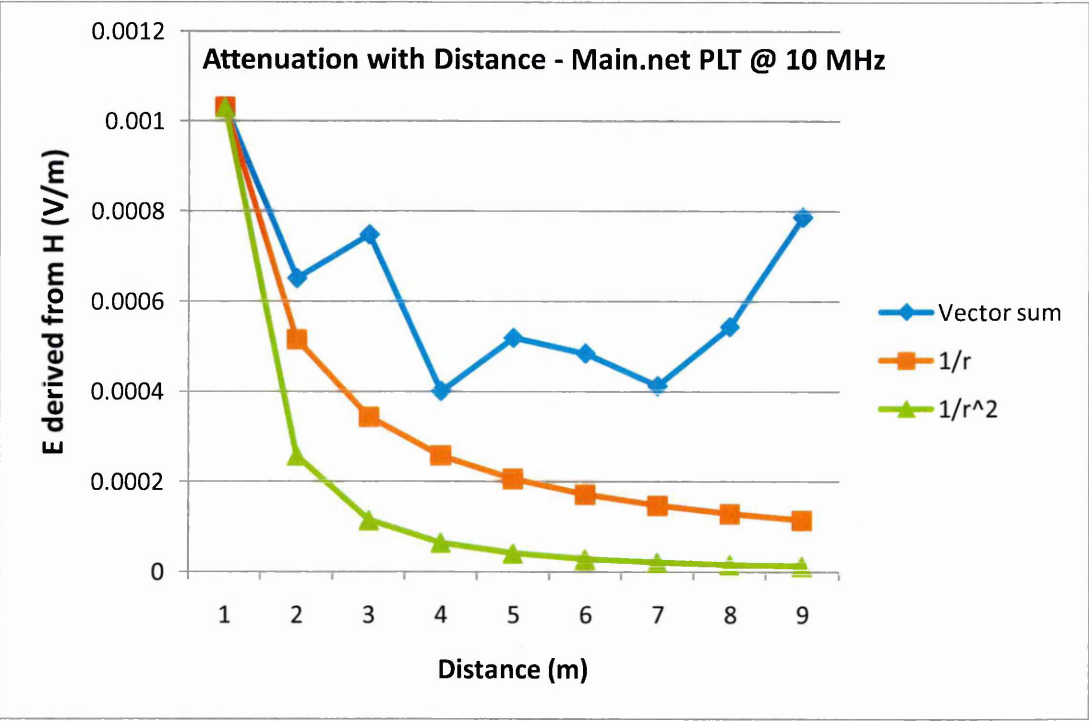


Figure 4-27 – Attenuation with distance of Main.net PLT @ 10Mhz

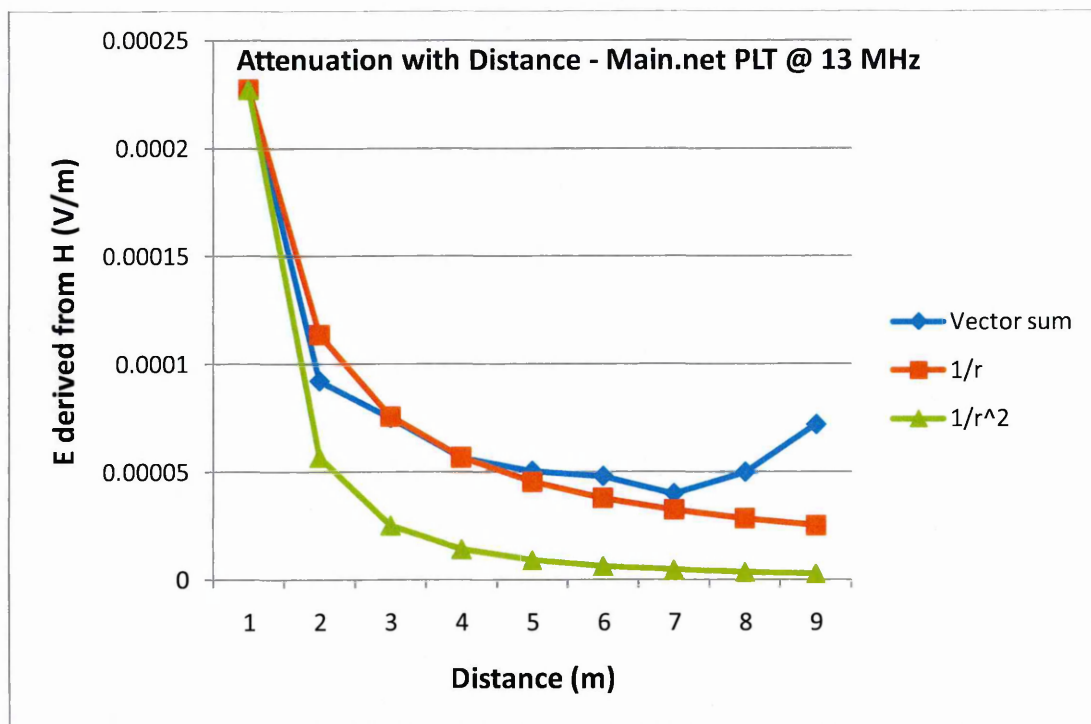


Figure 4-28 – Attenuation with distance of Main.net PLT @ 13Mhz

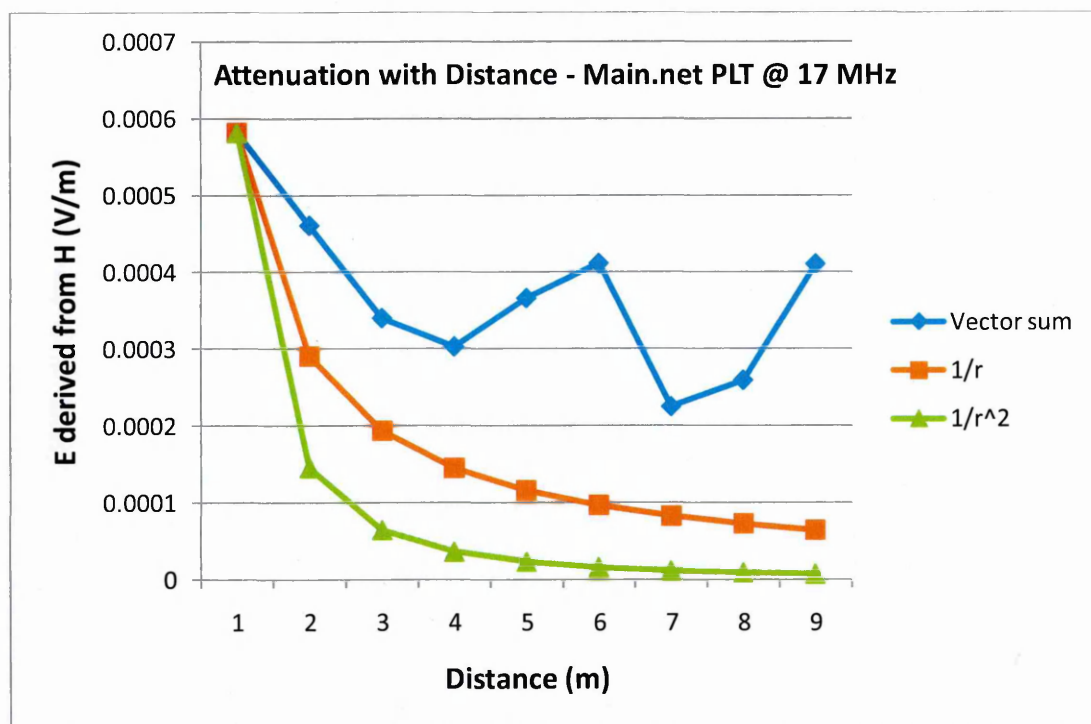


Figure 4-29 – Attenuation with distance of Main.net PLT @ 17Mhz

By comparing the graphs above with those of the attenuation with distance, one can see that the characteristics are similar. The average attenuation with distance is between $1/r$ and $1/\sqrt{r}$ and there are some standing waves at certain frequencies as the

contributions from other premises become significant. Although this is a limited data set and no firm conclusions should be drawn from it, one would expect that the characteristics of the environment (the house, neighbouring houses, ambient noise) would dominate over any fluctuations due to a differing modulation scheme.

4.7 MEASUREMENT 4 – NETWORK ANALYSER

4.7.1 Rationale

The attenuation with distance measurements discussed so far have given an insight into whether or not one can claim that the roll off with distance truly is $1/r$ under open area conditions when measuring in the near-field. The initial indication from the measurements so far is that the attenuation is somewhere between $1/r^2$ and $1/\sqrt{\text{distance}}$, however this is based on a single measurement campaign in an urban/semi-urban environment with a limited set of frequencies and distances. Ideally, one would wish to increase the number of measurement distances and also the number of frequencies; however the EMC equipment has to operate in a manual mode because for this test the signal analyser and the EMC receiver have to be programmed for each measurement distance. For normal emission measurements only the EMC analyser is controlled and it can be set to sweep the entire band with parameters set to determine the sweep time, number of frequencies and the time on each frequency.

In order to determine the generality of the measurements one would also wish to repeat the measurements in a number of locations to determine whether the effects of urban, semi-urban and rural environments are significant in the attenuation with distance figures. This would allow a general estimate to be made of the near-field/far-field boundary. Coupled with the manual measurement process and the desire to measure more frequencies and distances, an alternative measurement technique was sought. Ideally one would have written software to control both the signal generator and EMC analyser, but the signal generator was not externally programmable.

Investigations into the equipment available within the University inventory or to an affordable purchase of a new programmable signal generator concluded that the most cost effective option which did not compromise accuracy was to use an alternative piece of equipment – a Network Analyser.

4.7.2 Technique

The Network Analyser was an Anritsu 420B which is a Spectrum and Network Analyser Operating from 10Hz to 30MHz. Its use as a network analyser allows the entire system of mains network and antenna measurement system to be considered as a single four port network. When determining the attenuation with distance it is not required to know the “actual field strength”, just the relative field strength of readings compared to a previous distance. The Network analyser injects a signal into the mains network and measures the resultant voltage detected at the output of the antenna, compares it to the injected voltage and provides on screen in real time a graph of insertion loss across a frequency band. The Anritsu 420B is also General Purpose Interface Bus (GPIB) IEEE 488 standard compliant and therefore it can be controlled and data collected by a remote computer.

In order to control the network analyser it has to be connected to a control device using GPIB cabling. The control device in this case was a Pentium PC running Windows 98 which hosted a GPIB interface card in one of its Industry Standard Architecture (ISA) slots. Software (see Appendix E) was written using Delphi version 3 to control the analyser to sweep from 1.6 – 30MHz with a bandwidth of 1kHz and collect 250 data points. The resultant data was transferred back to the PC and saved as a user defined .csv file to allow it to be analysed in Microsoft Excel. Delphi was chosen because it is a visual language which allows the production of Windows style programs and is based on the Pascal programming language which the author was familiar with. As the program was only being used by the author it was kept simple and assumed to be

laboratory standard development software that required the user to follow a defined manual procedure.

The Anritsu 420B has 75Ω inputs as it was designed primarily for the TV communication market. When connecting to the mains network or the Schaffner/Wellbrook EMC loops 75Ω to 50Ω network adaptors and 75Ω cables were used as appropriate. The test setup is shown in Figure 4-30.

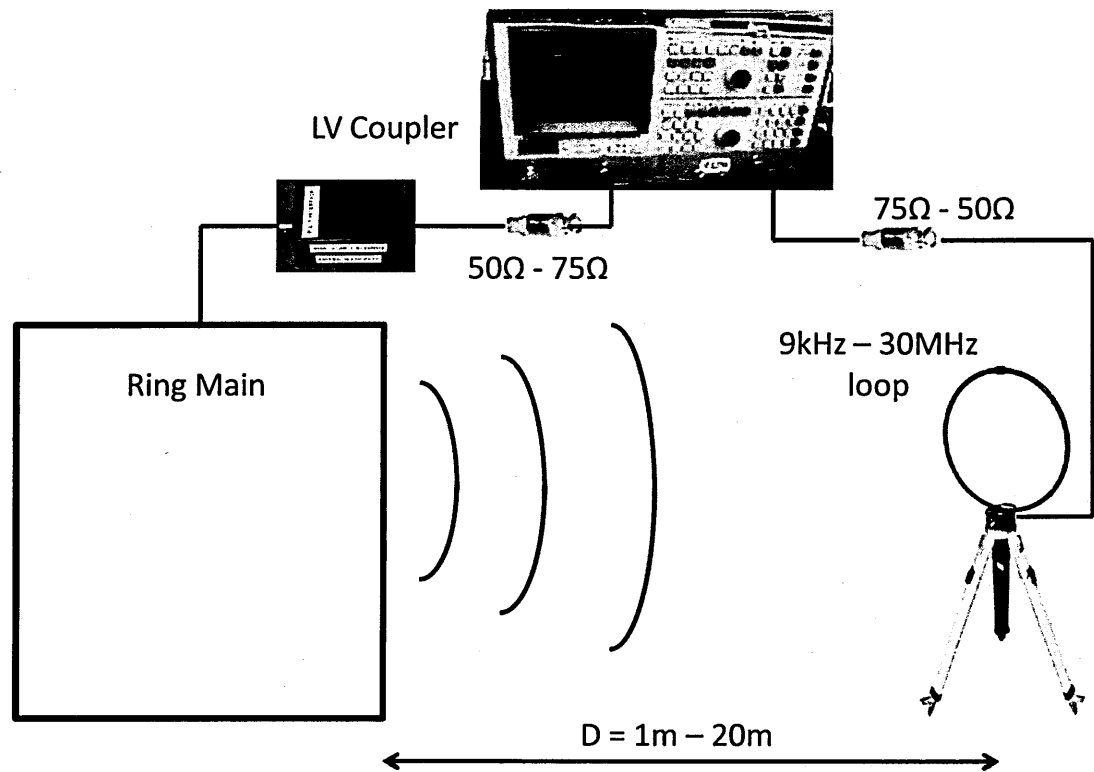


Figure 4-30 - Attenuation with distance using network analyser – setup

The frequency range and bandwidth were set as per other EMC measurements, although the duration had to be determined. As the aim was to take each measurement ten times and come up with the average value, the sweep duration was determined by the settling time of the analyser from the specification and consideration of the amount of readings to be taken (250). After initially concluding that a 1 minute sweep duration was within the performance of the analyser, a test was conducted with a sweep duration of 10, 60 and 300 seconds to determine the variability in insertion loss. As can be seen from Figure 4-31, all readings are within 1dB at most frequencies and at most

separated by 3dB. A sweep duration of 60 seconds was chosen as a compromise between acceptable accuracy and duration of overall testing.

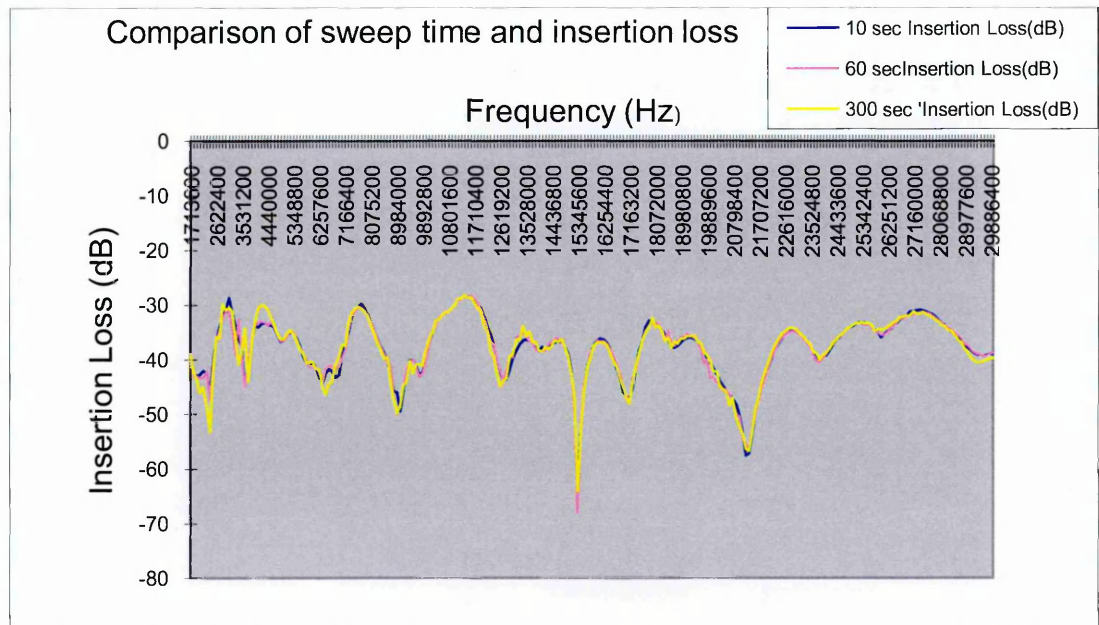


Figure 4-31 – Comparison of sweep times to determine optimum

The test software prompts the user to undertake a calibration run which measures the cable loss, the loss in the 75Ω/50Ω couplers and any inherent noise in the analyser, which is internally subtracted from the final measurement. An area of difficulty in using a network analyser is that accounting for the ambient noise is more difficult because one has to inject something to obtain an insertion loss. This was considered at the outset but the aim of the test was to take as many readings as possible in as many locations as possible and determine from observation of graphs any patterns that may help identify the near-field/far-field boundary. When each graph was checked a comparison was made of perpendicular to parallel orientation for obvious noise spikes, because high level ambient peaks from intentional radiators tend to be detected in all orientations. The overall errors are therefore in the main systematic and, because the actual measured value is not important, these can be ignored. The areas of random measurement that need to be considered are those of variability of ambient noise as discussed.

The test was conducted in three locations representing urban, semi-urban and rural and also covering a domestic premises and an industrial premises. At each location measurements were taken in the perpendicular and parallel orientation to provide the vector sum as before. As each test would measure 250 frequencies, at 20 distances in 2 orientations the presentation of data was going to be time consuming. A further software program was written in Delphi that took as input a .csv file containing the data and reduced it to 30 frequencies at 1MHz increments. It then plotted by frequency as a batch and output 30 graphs in Windows Metafile (.WMF) format that could later be converted to whatever graphics format was required.

4.7.3 Results 10 – Urban premises – Bradley Stoke.

The same test location as mentioned in paragraph 4.5.3 was used as the urban test location. The measurements took place on the 3rd October 2006. The graphs of the vector sum of the parallel and perpendicular orientations of 30 (between 1.6MHz and 30MHz) of the 250 test frequencies are shown at Appendix F. The first conclusion to be drawn from the graphs is that they follow a pattern of that seen the previous year when using the EMC analyser and signal generator at spot frequencies. At the lower frequencies when one is certain to be in the near-field then the field pattern does not represent that of a plane wave. There is also the recognition that once the antenna is moved away from the premises that other houses and the upstairs component of the house under test make a contribution to the field pattern and standing waves occur. On this test, and also if one looks at the results of the antenna in its parallel or perpendicular orientation only, one can see that the attenuation curve approaches $1/r$ or $1/\sqrt{r}$ at around 12MHz. At frequencies above 20MHz and at greater distances, there appears to be disproportionate increases in field strength which becomes significant. One reason for this may be that all antennas have a resonant frequency at which they will transmit and receive power. If one considers the mains network to be a complex antenna then it is reasonable to assume that it will have some frequency where it will

have optimum power transfer and therefore there will never be a mathematically pleasing (e.g. $1/r$) graph until the measurement distance is much greater than the dimensions of the structure.

4.7.4 Results 11 – Semi-Rural premises – Bridgwater.

The tests were also undertaken at Bridgwater College in Somerset, UK on 18th March 2006. Because of its geographic location, Bridgwater can be considered to be semi-rural as it is large town but some distance from any other major towns. The college was an interesting test premises because it had both three-phase and single-phase architectures and a range of classrooms and workshops. It was also chosen as access to it was permitted through consent with a colleague. Figure 4-32 shows the location of the college and the building in question where measurements were taken from. The building was a laboratory used to teach electronics.

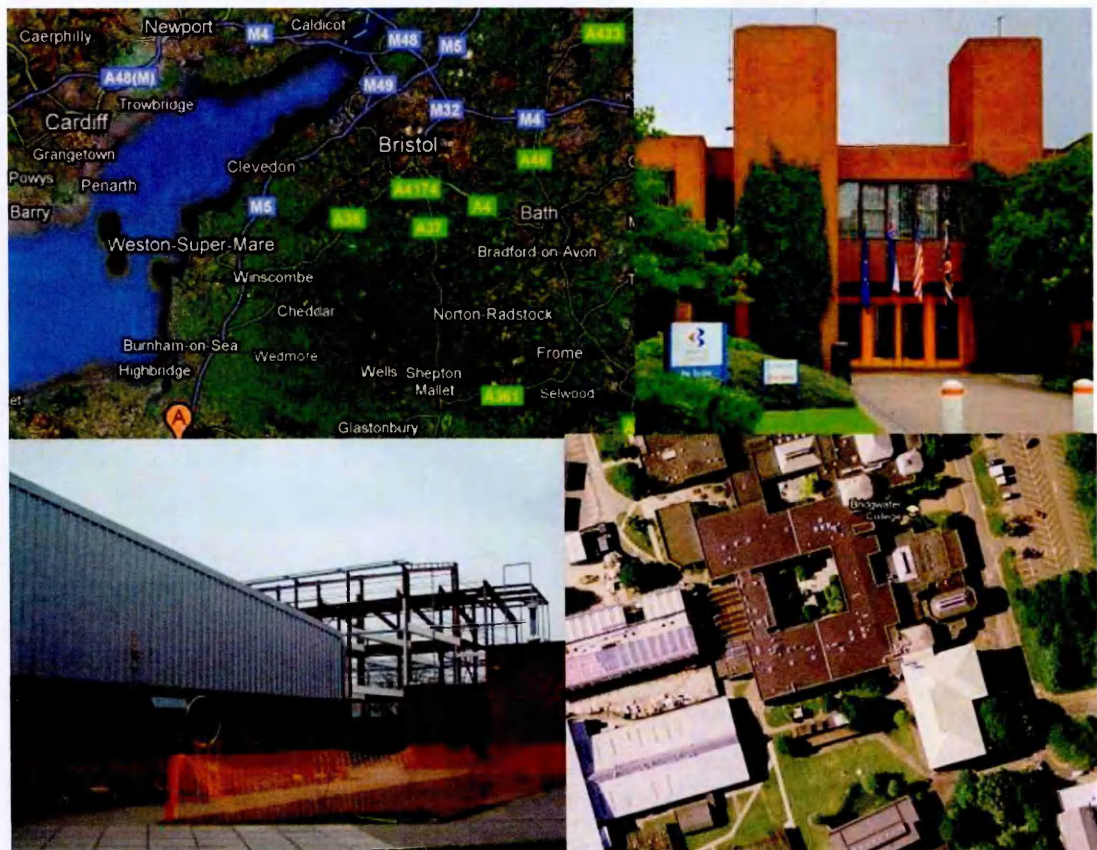


Figure 4-32 – Bridgwater College, Bridgwater, UK – site location

The test method was the same as mentioned for Bradley Stoke, although measurement distances were limited to 12m due to a cordoned off area that was due to become a construction project although there was no buildings within 25m of the source. At the time of the measurement, the college was closed and therefore all computers and equipment would have been powered down. The graphs are shown in Appendix G. The observation from these results is that the roll off was more predictable than in the urban case and there were less standing waves, probably as there were fewer collocated buildings to the measurement site. Even at low frequencies the attenuation with distance graphs followed the expected $1/\sqrt{r}$ to $1/r$ roll-off. The other observation is that in the Bradley Stoke measurements there was a lower electric field strength within the first 2m which increased as the antenna was moved from the premises. At Bridgwater the highest signal levels were close to the building. It is assumed that this is because Bridgwater is a single storey building whereas Bradley Stoke was a two storey building that had an upstairs contribution as the antenna moved away from the premises. Like the results for Bradley Stoke there were apparent frequencies where a more effective radiation took place, and it was also noted that at higher frequencies above 20MHz the roll-off with distance was almost linear rather than as $1/r$.

4.7.5 Results 12 – Rural premises – Milton Keynes.

The final set of tests were conducted at The Open University Campus in Milton Keynes, Buckinghamshire, UK on the 2nd May 2006. Although Milton Keynes is a large, new town, the Open University is situated on the outskirts. Furthermore there is a single building student accommodation, known as Park Corner Cottage, which has no major buildings around it for 50m, with the exception of a small dwelling to the rear which was believed to be uninhabited at the time of the test. Ideally a full rural test would have been undertaken but access to such a property could not be secured. The location and premises are shown at Figure 4-33.



Figure 4-33 – Open University, Milton Keynes, UK – site location

The test methodology was identical to the Bradley Stoke method including distances. The results are shown in Appendix H. Like the Bradley Stoke measurements the attenuation with distance pattern was not predictable at the lower frequencies. It did however begin to become predictable from around 5MHz, at a measurement distance closer to the premises than the equivalent measurement at Bradley Stoke but further from the premises at Bridgwater. Overall, when ambient spot frequencies are accounted for, the Milton Keynes premises showed a general $1/\sqrt{r}$ roll-off. Of all the measurement locations, it showed the most predictable behaviour across a wider range of frequencies. It also, as expected, had fewer very high value individual spikes, presumably because there were no other contributors in the vicinity.

Each of the three measurement locations had specific roll-off curves at specific frequencies but the common elements appear to be that other premises connected via a common network contribute to PLT radiation. The shape and architecture of each premises has a fundamental effect on the frequencies at which maximum radiated

emissions occur. The roll-off curves are not necessarily as predictable as one would hope leading to a variation in where the near-field/far-field boundary is. Standing waves occur and the distance of maximum radiated emission is not necessarily at the closest point to the victim receiver. A full summary of all measurements will be provided in Chapter 5.

4.8 MEASUREMENT 5 - MUTUAL INTERFERENCE

4.8.1 Rationale

The original aim of this research was to attempt to identify a “safe limit” for PLT that would allow coexistence with other services. The results obtained so far in this research and in measurements by others make it highly unlikely that an agreed safe limit could ever be reached that accounted for a signal to noise ratio acceptable to the radio amateur community and also to allow PLT to be rolled out. As has been demonstrated so far, because the roll-off with distance is a function of each premises and is quite unpredictable it becomes almost impossible to determine a “safe limit”. It has become apparent that the only limit that will be agreed will be a “compromise limit” and therefore the question to be answered is “what is an acceptable compromise?” To answer this question one must accept that with such variation on locations, technology and environment, predicting a compromise using theory or extrapolating from measurements is very challenging.

With this in mind, an investigation was undertaken to determine alternative EMC test methods that allow a more subjective assessment when the test environment is not ideal. A technique used by the military is mutual interference testing. In fighter aircraft for example, best engineering practice of running cables at 90 degrees to each other is impractical. Furthermore, to undertake EMC measurement inside a small aircraft with lots of systems is impossible. The concern in aircraft is that a flight critical system can be overcome by a radiated emission from another system and cause a catastrophic

failure. To baseline these effects, new aircraft that enter service are subjected to mutual interference testing. The key components are monitored using current clamps and subjected to large radiated fields to determine at which point the flight safety critical components fail. When an aircraft is modified in service, current clamps can be placed around the critical components and the new equipment switched on to determine the increase over the baseline of the conducted field.

A similar technique could be used for PLT, to determine when a victim receiver becomes affected by the radiated emissions from PLT to the extent that it cannot complete its function. This is not necessarily at a signal to noise level agreed as acceptable by a standards body such as the ITU, but at a level that is mutually acceptable to both parties.

4.8.2 Technique

The technique that was decided upon was to find a broadcast station and tune into it using a standard HF receiver. At various distances from a premises using PLT, the electric field strength could be measured using an EMC receiver and a subjective assessment of the degradation of the signal could be undertaken. Ideally for a standard test one would require a random sample of ages and sexes to determine what was acceptable as is done for audiometric tests, however for this test the available testers were male between 35 and 60 years old. The test layout at Figure 4-34 was set up at Milton Keynes at the same location that was used for the regression testing.

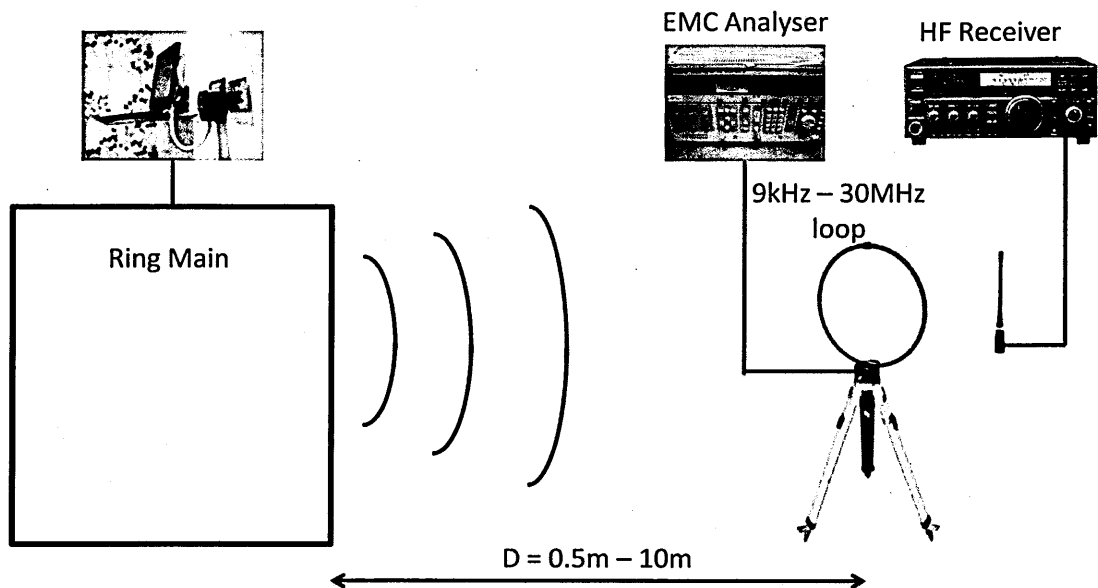


Figure 4-34 – Mutual interference test – setup

The PLT system used was an in-house system from Devolo which used OFDM as a modulation scheme and Carrier Sense Multiple Access/Collision Detection (CSMA/CD) as its protocol. The HF receiver was an Icom 728 and a standard monopole was used as the test antenna. It is recognised that a normal HF user would have a fixed arrangement with greater sensitivity but as this was a proof of concept demonstrator and had to be mobile, a standard antenna was used, which was tripod mounted at 1.5m. Separation was kept from the loop antenna by 3m, ensuring that the distance from the premises was the same to the loop as to the monopole. A list of test frequencies was identified that produced good quality reception under ambient circumstances. It was not possible to determine the location of the transmission, but the languages provide an indication that the reception was from a distance that makes the test credible (Table 4-19).

Frequency (MHz)	Modulation	Notes	Quality
6.113	AM	English	excellent quality
7.309	AM	Eastern European	good quality
9.309	AM	Eastern Asia	good quality
11.785	AM	Eastern Asia	good quality
13.671	AM	French	good quality
15.126	AM	Eastern European	excellent quality
17.897	AM	European	excellent quality

Table 4-19 – List of test frequencies

In order to make the subjective assessment the following definitions were agreed on and used by each member of the assessment team (Table 4-20).

Normal	PLT cannot be heard and the received signal sounds as the original
Acceptable	PLT can be heard but it does not degrade the quality of the signal
Tolerable	PLT can be heard. The original signal can still be heard but the sound of PLT is annoying
Unacceptable	Background signal can be heard but in the main is unintelligible over the PLT noise
Loss of Sound	PLT has overcome signal and original signal cannot be heard.

Table 4-20 – Definitions for sound quality

At the outset, a sweep of the ambient noise and also a sweep with PLT on at 3m was taken to provide an indication of the emissions from the PLT (Figure 4-35). A file transfer was set up between two laptops to activate the modems.

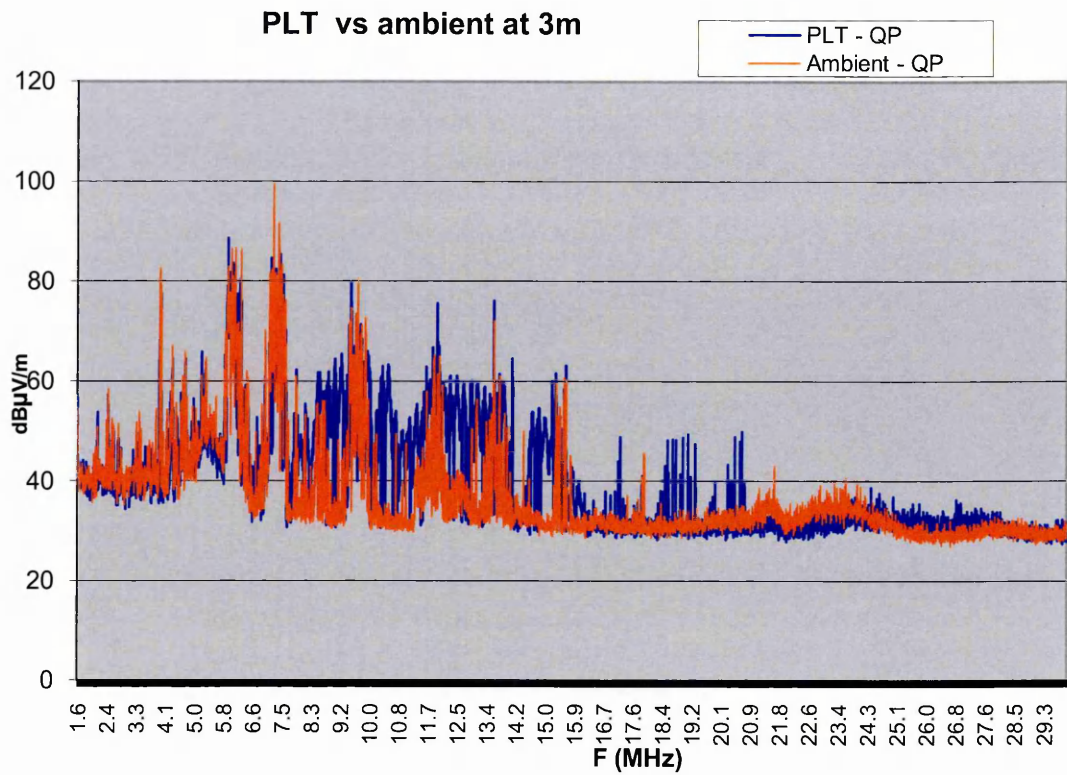


Figure 4-35 – PLT vs ambient as baseline for mutual interference test

4.8.3 Results

The tests were intended to be run to distances out to 10m but it became apparent that the PLT noise had little or no consequence beyond 7m. Table 4-21 shows the frequencies under test that had a reference signal to test against, the measured quasi-peak value on the EMC receiver and also the subjective assessment of the three individuals that were present.

Frequency (MHz)	Distance	E (dBµV/m) - QP	Sound Quality
6.113	1m	78.3	Unacceptable
6.113	2m	76.8	Unacceptable
6.113	3m	73.0	Tolerable
6.113	4m	69.5	Acceptable
6.113	5m	68.6	Acceptable
6.113	6m	67.0	Normal
6.113	7m	52.8	Normal
7.309	1m	73.9	Unacceptable
7.309	2m	69.0	Tolerable
7.309	3m	66.1	Acceptable
7.309	4m	64.4	Normal
7.309	5m	64.1	Normal
7.309	6m	63.4	Normal
7.309	7m	59.8	Normal
9.309	1m	35.4	Tolerable
9.309	2m	34.9	Acceptable
9.309	3m	34.4	Acceptable
9.309	4m	34.1	Acceptable
9.309	5m	32.0	Normal
9.309	6m	32.1	Normal
9.309	7m	29.8	Normal
11.785	1m	45.1	Loss of Sound
11.785	2m	43.2	Loss of Sound
11.785	3m	40.0	Unacceptable
11.785	4m	41.2	Unacceptable
11.785	5m	39.7	Unacceptable
11.785	6m	36.1	Tolerable
11.785	7m	32.3	Acceptable
13.671	1m	44.4	Tolerable
13.671	2m	45.6	Tolerable
13.671	3m	40.3	Acceptable
13.671	4m	39.6	Acceptable
13.671	5m	38.7	Acceptable
13.671	6m	37.1	Normal
13.671	7m	37.6	Normal
15.126	1m	46.2	Loss of Sound
15.126	2m	40.1	Unacceptable
15.126	3m	40.3	Unacceptable
15.126	4m	35.2	Tolerable
15.126	5m	35.0	Tolerable
15.126	6m	34.6	Tolerable
15.126	7m	30.2	Acceptable
17.897	1m	45.6	Tolerable
17.897	2m	43.2	Acceptable
17.897	3m	42.5	Acceptable
17.897	4m	42.3	Acceptable
17.897	5m	41.0	Acceptable
17.897	6m	39.9	Normal
17.897	7m	38.7	Normal

Table 4-21 – Assessment of interference to wanted signal

The conclusion was that in general the signal became acceptable beyond 3m but to guarantee an acceptable sound quality, such as it was intended, the distance from the victim would have to be around 6m. This test, of course, has chosen intentional radiators that have a good quality signal and it should be recognised that an amateur user using a sensitive receiver and antenna combination would probably require a larger separation distance. In reality this may not be such an issue as many radio amateurs would choose to place their antennas some distance from the premises to reduce general ambient noise. The other observation was that an acceptable or tolerable signal level occurred when the PLT signal was not greater than the intended radiator by more than 5-10dB μ V/m. Of course this is specific to this test only and is a function of the PLT modulation scheme and the receiver set up used.

4.9 MEASUREMENT 6 – K FACTOR

4.9.1 Rationale

The final measurements to be undertaken were to determine if there is a value for K-factor which can be used to determine the radiation from a mains network based on PLT. As mentioned in Chapter 2, other researchers have attempted to derive a value, however to date correlation between various measurements has not resulted in consistent results. To determine the K-factor one would want to measure only the contribution from the mains and not the contributions from other sources. Equally to determine the K-factor one would also want to be sure that the entire portion of the emitted radiation that would be at the measuring point should be included. Other researchers have omitted these and therefore the aim was to apply these assumptions and derive a value for K factor. Others have measured K-Factor at 1m or 3m but in fact it can simply be calculated for all frequencies if one is undertaking regression measurements.

4.9.2 Technique

No additional measurements were required as the source data from paragraph 4.5.6 was used. To be able to calculate the K Factor one must know the measured voltage in dBμV/m and the injected voltage in dBμV. To convert from V to dBμV the following equation was used:

$$V(\text{dB}\mu\text{V}) = 20 \log (V) + 120 \text{ (noting } 0 \text{ dBV} = 120\text{dB}\mu\text{V} = 1\text{V)} \quad (4-4)$$

For the two injected voltages used in this test, 20V equates to 146 dBμV and 100mV equates to 100 dBμV. To then obtain the K-factor one subtracts the input voltage from the measured voltage. The following graphs (Figure 4-36 to Figure 4-39) show the K factor for each measurement distance.

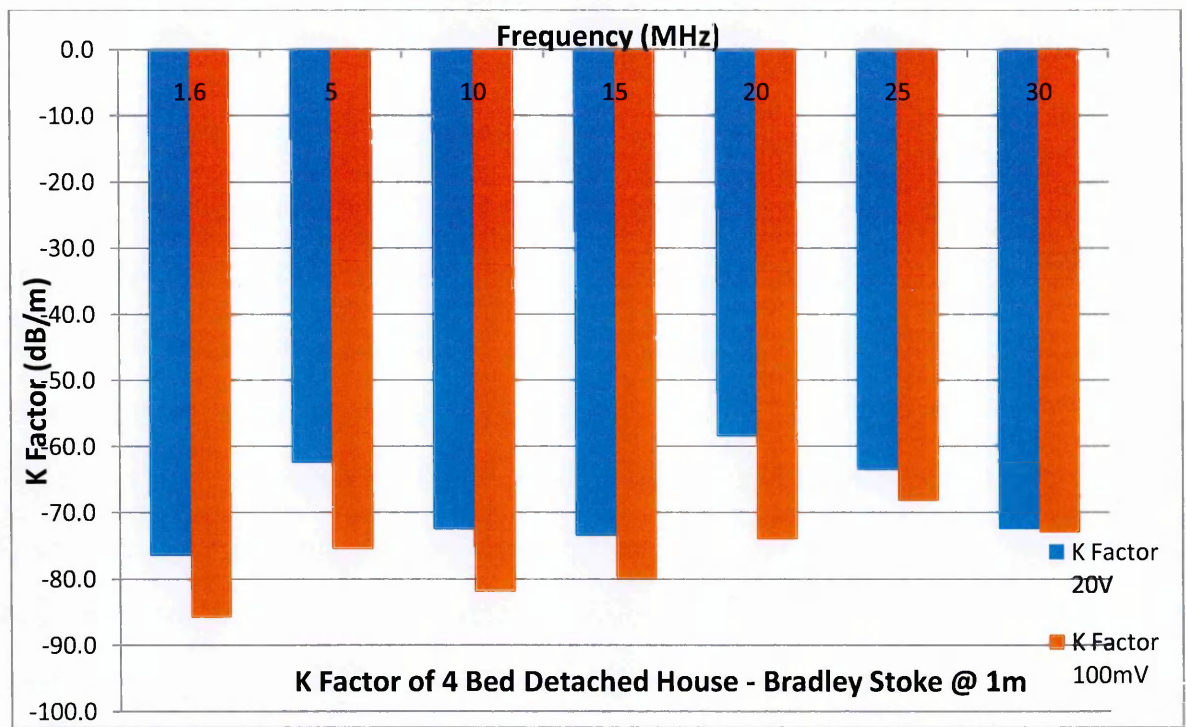


Figure 4-36 – K factor, 4 bedroom house, Bradley Stoke, UK @ 1m

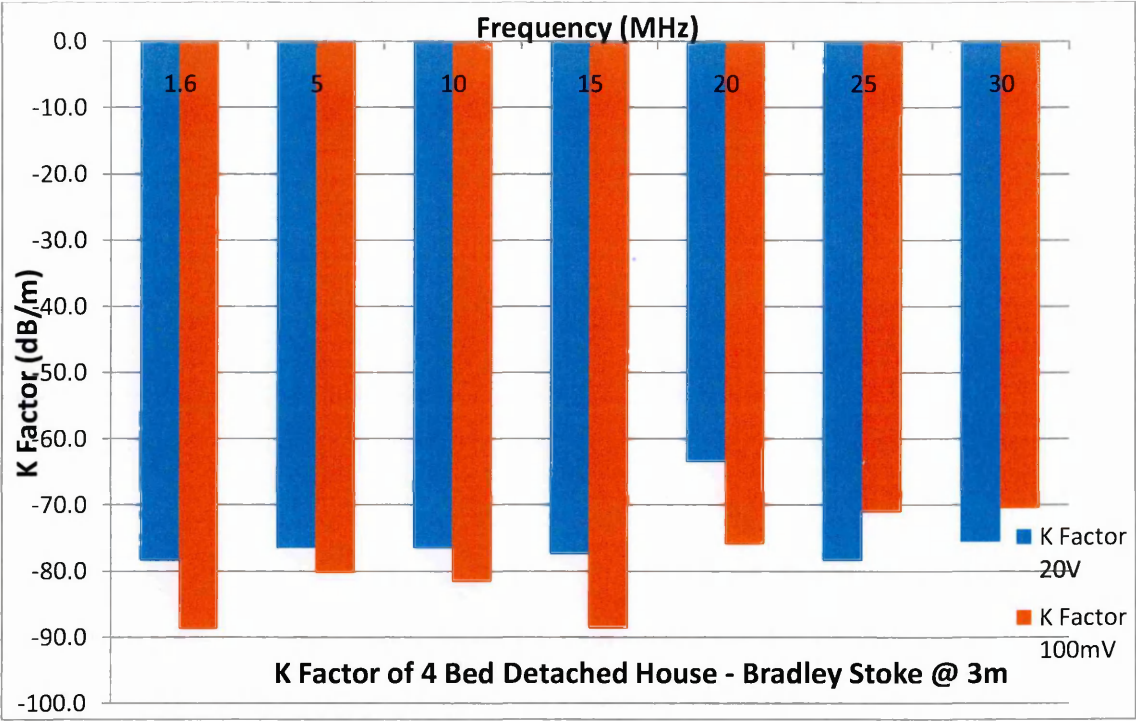


Figure 4-37 – K factor, 4 bedroom house, Bradley Stoke, UK @ 3m

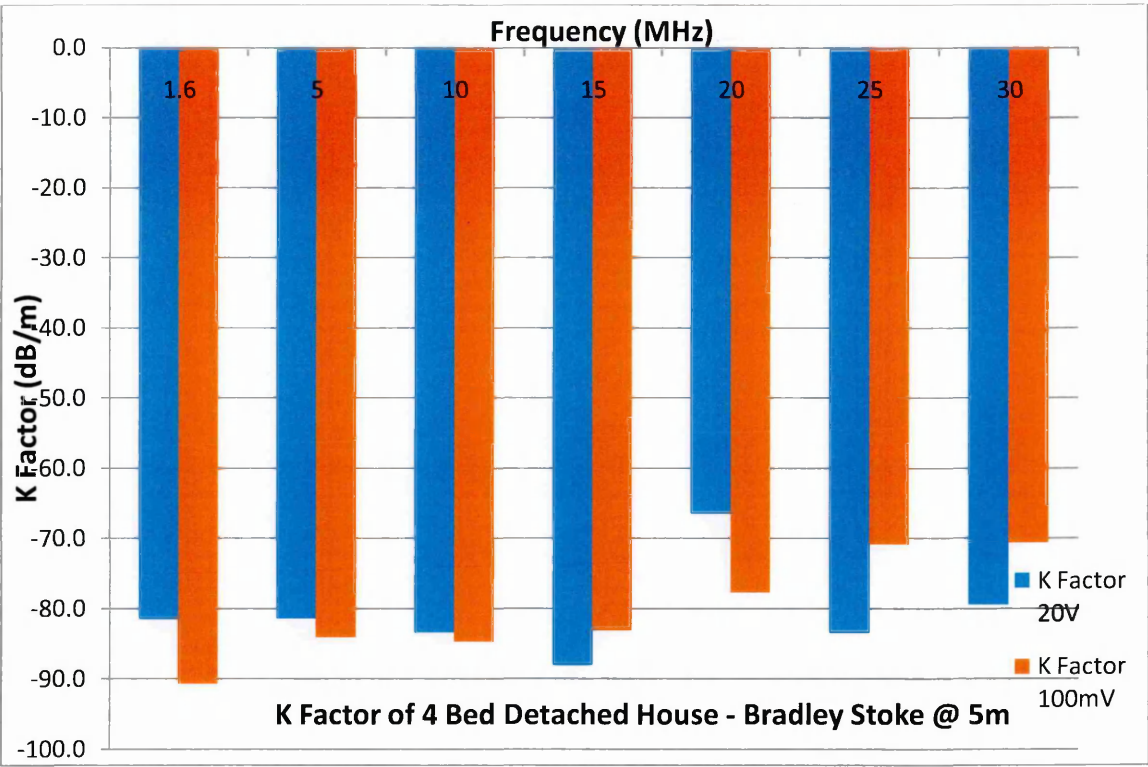


Figure 4-38 – K factor, 4 bedroom house, Bradley Stoke, UK @ 5m

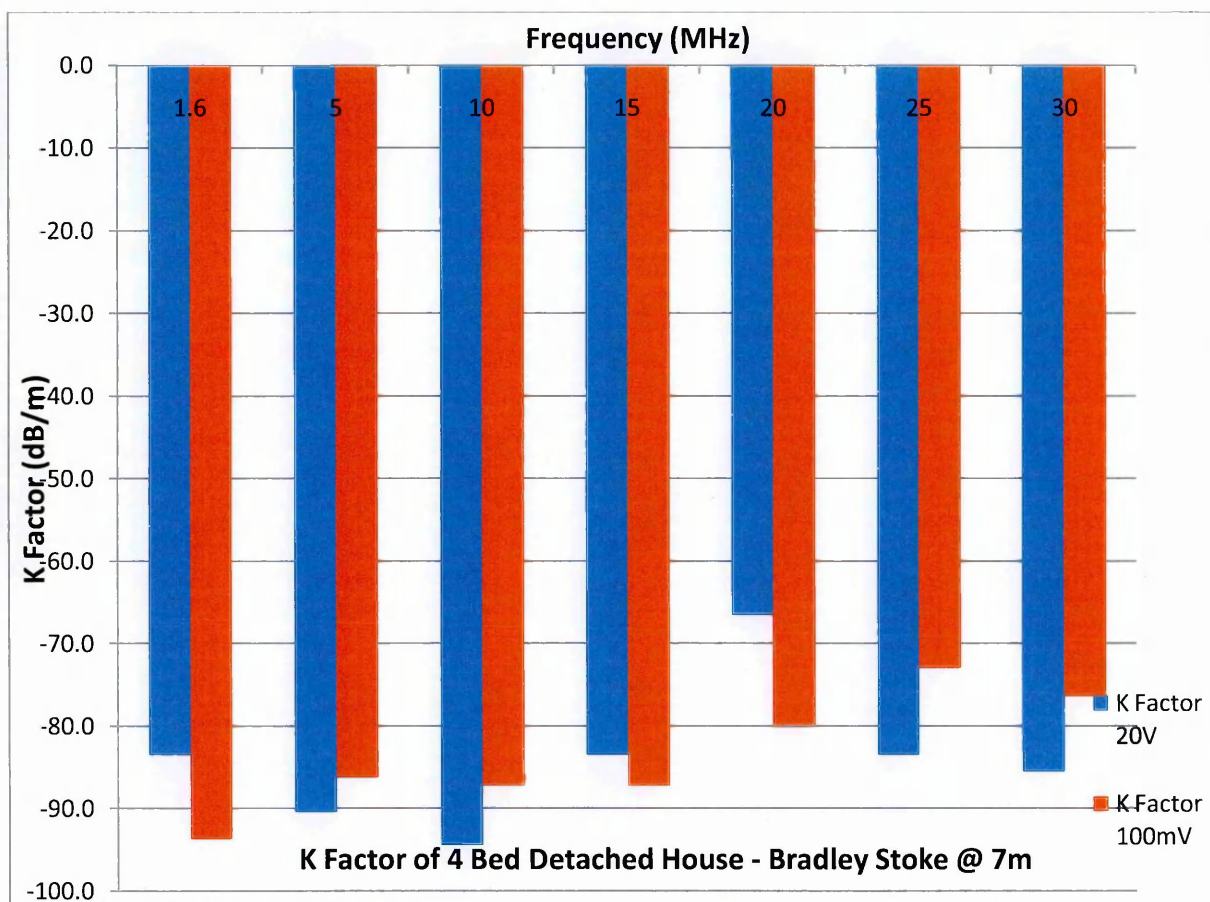


Figure 4-39 – K factor, 4 bedroom house, Bradley Stoke, UK @ 7m

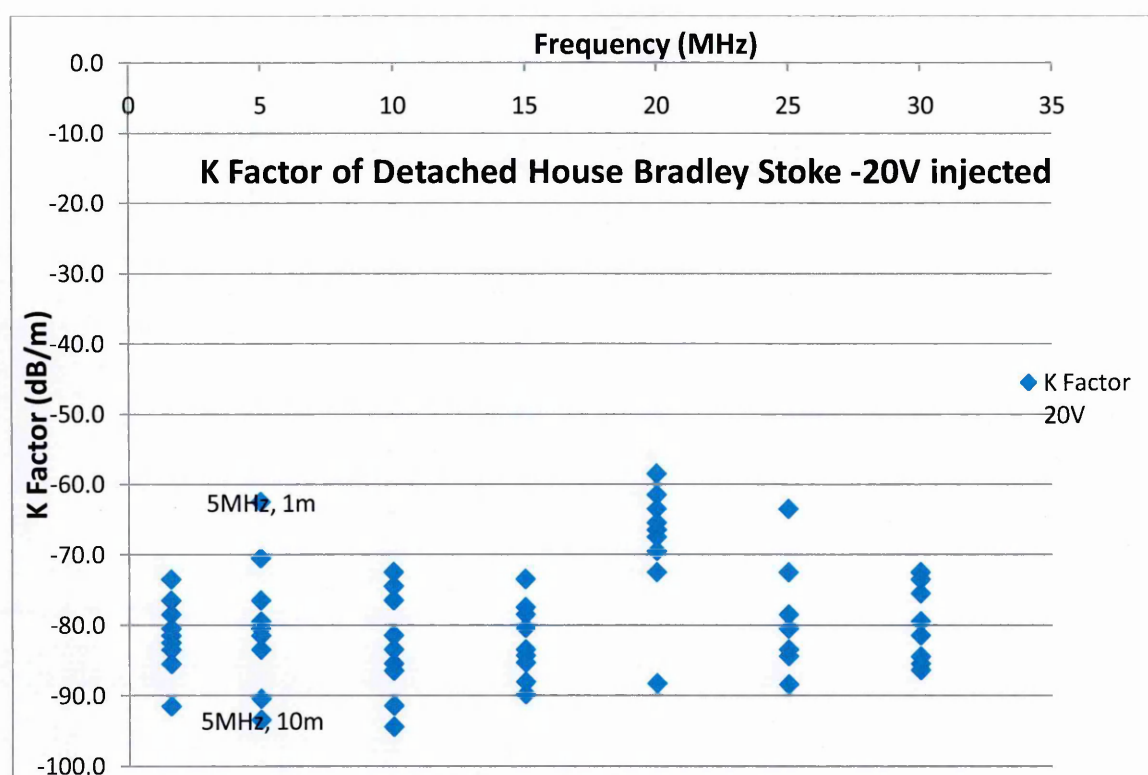


Figure 4-40 – K factor, Bradley Stoke, UK @ 20V showing all distances

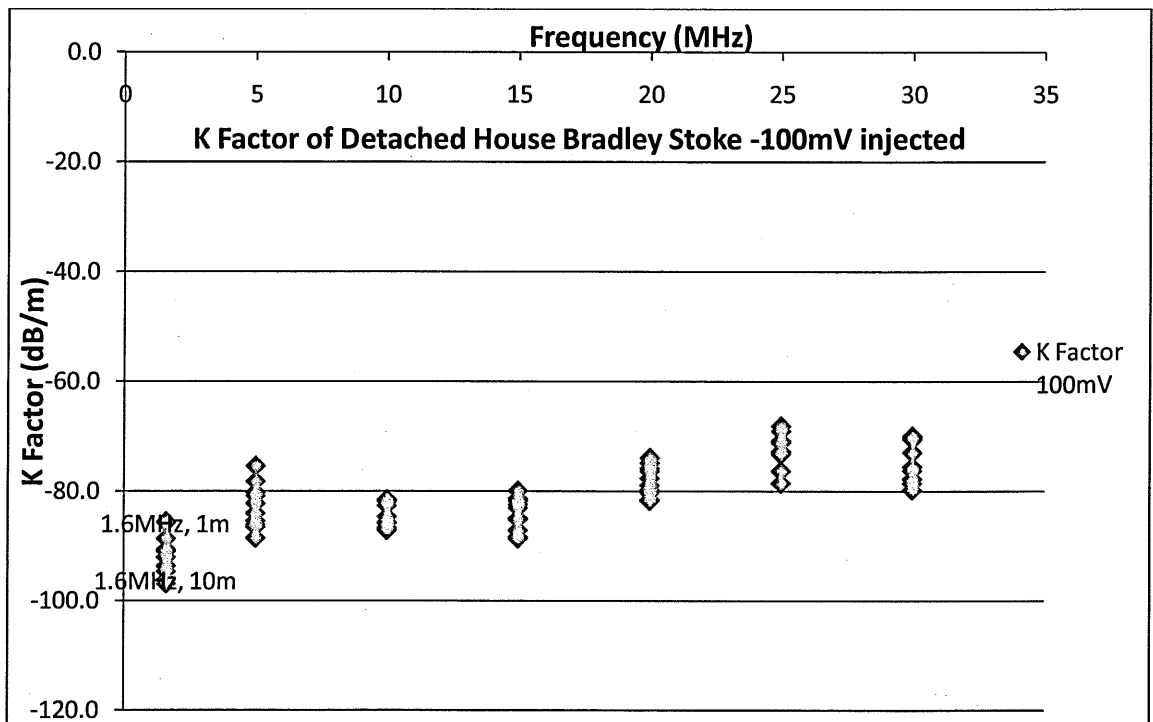


Figure 4-41 - K factor, Bradley Stoke, UK @ 100mV showing all distances

From the graphs above, a number of conclusions are drawn. Firstly, the measurement distance has a significant effect on the K factor because, as has been observed with all measurements, the radiated field changes with distance and therefore without a standard distance the notion of K factor is meaningless. The spread of data points in Figure 4-40 and Figure 4-41 clearly show how for each frequency the K factor changes with distance. Secondly, there is a difference in the K-factor that is determined by the injected voltage and without a standard voltage, its use as a predictor of radiated emission is of little value. Thirdly, other researchers had been hoping to determine a number in dB/m that is the typical K-factor for a house. Clearly this is impossible because the K-factor, which is analogous to antenna factor, is frequency dependent. It is accepted that all antenna have a natural frequency band that is a fundamental property of their size, shape and loading at which they are more efficient and therefore there can never be a single K-factor. At best the K-factor could be supplied as a graph that covered the frequencies of concern. All antenna factors are calibrated in a known environment such as an OATS. For the measurements presented here, the ambient

noise has been removed (which is as good as can be achieved in urban areas) and as a consequence the numbers in question are 20-30 dB/m different to others, but are believed to have a greater level of accuracy.

In summary, the variability of the field measurement process (non-standard distance, orientations and injected voltage) and the associated emitted radiation make the calculation of the K-factor an erroneous activity. Initially it was seen as a method for correlating conducted emissions with radiated emission, but it is concluded that the use of the K-factor to achieve this has little merit.

4.10 SUMMARY

Other researchers have undertaken measurements of radiated emissions at PLT test sites but due to constraints of time on site have only been able to undertake certain measurements. The measurements presented in this chapter have attempted to repeat measurements changing only one variable to determine the accuracy of the measurements of others. Specifically, the assumption that attenuation of the electric field with distance has long been considered to be $1/r$ – something that to date has not been systematically determined in a non-calibrated site. The results of a targeted campaign of attenuation with distance measurements have been presented that vary location, antenna orientation, injected power and direction from premises. Furthermore, using these results the K-factor has been calculated and a limited assessment of its utility has been undertaken. Finally, an alternative notion of mutual interference testing has been presented that may have utility in the final determination of a “safe” or “acceptable” limit for radiated emissions. Chapter 5 analyses these results in more detail and in the context of determining an “acceptable” limit.

CHAPTER 5 - SUMMARY OF RESULTS

5.1 INTRODUCTION

Chapter 4 presented a number of individual results that may go some way to inform standardisation bodies of an acceptable limit for radiated emissions from PLT. It is worth looking at these in the general sense and also in the context of setting an acceptable limit. Once these had been considered, the challenge of this research was to attempt to determine an acceptable limit to assist standardisation bodies. Since this research was undertaken it has become apparent that there will be a number of non-engineering considerations that will shape future regulation and these are discussed in Chapter 6 in some detail with the aim of determining an acceptable limit and in-service compliance strategy.

5.2 SUMMARY OF RESULTS

The results detailed in the previous chapter, although interrelated, can be considered as three individual topics and will be summarised as such.

5.2.1 Radiated Emission Measurements

The measurement of ASCOM and Main.net modems at Maidenhead in the UK (paragraph 4.4.4) highlighted an important effect. Firstly that the ASCOM modems had a peak signal strength at 1m of 80dB μ V/m compared with 65dB μ V/m for the Main.net modems. This is probably brought about by the modulation scheme for Main.net having a wider bandwidth and spreading the available transmit power across a wider spectrum. A comparison of Main.net modems operated in Linz, Austria (paragraph 4.4.5) showed that in general the radiated emission had the same amplitude and spectral pattern as when operated on a UK network. In both cases the radiated emission is superimposed on the underlying noise floor and therefore large radiated emissions are not solely due to the PLT modem. To demonstrate this further a comparison was made of the ambient noise in the 16MHz to 30MHz band in the UK,

Austria and Australia (paragraph 4.4.6). In the cases of UK and Austria, because they are densely populated and are affected by other intentional radiators from around Europe, their spectral pattern demonstrates significant noise across the band from 1.6MHz to 22MHz. In contrast, Australia has a relatively low noise floor with specific bands allocated to intentional radiators.

Overall there have been a number of radiated emission measurements taken on PLT systems across the world but the correlation of results is not straightforward due to differences in measurement technique and distance. The body of evidence of radiated emissions tests conducted in the UK by others such as OfCom have been complemented by the OU PSCRG measurements overseas by using the same technique. Although each modem type has a different modulation scheme one can generalise that the effect of PLT modems compared to the ambient noise is to raise the surrounding noise floor by an average of 10dB μ V/m across the band with peaks in certain areas of up to 40dB μ V/m. For some modulation schemes such as those used by DS2, these peaks can be multiples of MHz wide. There are, however, a number of errors associated with these measurements and one should conservatively expect to quote an average error of ± 8 dB with errors of ± 15 dB possible under certain conditions.

Associated with the PLT emission results was the observation that the noise floor in different locations is significantly different and therefore the prediction of signal to noise ratio is not straight forward. In densely populated areas the overall ambient noise is higher and has a number of impulses that would have an effect on a victim receiver and these are already avoided by those monitoring low level signals.

5.2.2 Attenuation With Distance Measurements

One of the main themes of this research was to determine the attenuation with distance of a number of premises in different locations and environments but using a repetitive

technique to make changes to a single variable. Initially, a manual method was used at urban premises (paragraphs 4.5.4 - 4.5.7) to investigate the variation of antenna distance and orientation on attenuation with distance. When measuring firstly with the antenna in a perpendicular orientation it was observed that at frequencies that one would expect to be in the radiated field the roll off was $1/\sqrt{r}$ rather than $1/r^2$. However it is difficult to draw conclusions from this because at higher frequencies there were very significant standing waves particularly at a distance from the premises. When the measurements were repeated with a parallel antenna, the attenuation with distance graphs ranged from $1/\sqrt{r}$ to $1/r^2$ but were generally more well defined with less standing waves. This is presumed to be because the antenna was orientated to premises such that it was not an effective measuring device and the measured emission was from surrounding premises. When the vector sum of the perpendicular and parallel measurements were calculated the overall results were more predictable and approached a $1/r$ attenuation with distance. One might conclude that for in-situ PLT measurements a vector sum more accurately measures the true radiated field at a measuring distance. The measurements were also repeated with monopole antenna

A limitation on the manual measurement is the number of frequencies that can be measured at each distance. A repeated set of measurements using a network analyser demonstrated that the attenuation with distance effects are similar across the 1.6MHz to 30MHz band but there are defined frequencies and distances that one may presume are approaching the far-field where there are disproportionately high radiated emissions. The possible causes of this are resonance of the mains at those frequencies, a contribution from other premises or a contribution from other circuits in the premises under test. When the measurements were repeated at semi-rural and rural premises the conclusions were the same as for the urban premises although with a variation on the specific frequencies where standing waves would occur.

In summary, the key observation is that one must attempt to negate the effects of ambient noise by subtracting the ambient from the measured to have any possibility of determining attenuation with distance. Furthermore, measuring only the electric field in a single orientation is acceptable for far-field measurements but in the near-field leads to very erroneous results. Measuring in multiple orientations and calculating the vector sum of the electric fields leads to attenuation with distance plots that one may expect but not at all frequencies. One of the key observations that has not been discussed in other research to date is that there is the likelihood of standing wave patterns when measuring in-situ due to multiple contributions from other premises, reflections and the contribution from each mains element of the premises under test. The conclusion is that one cannot assume any type of roll-off with distance with any certainty, and if one wishes to use roll-off with distance in any predictions one should at least note the potential errors. Taking this into account the roll-off with distance across all premises measured was between $1/\sqrt{r}$ and $1/r$ which was not expected. Near-field measurements in an open area site would normally have components approaching $1/r^2$ but these were not common in this measurement campaign. One should therefore conclude that PLT radiation at distances less than 20m is likely to have a roll-off with distance less than the 20dB/decade that is predicted and in theory would cause interference at distances further from PLT than one may expect.

The question of the whereabouts of the near-field/far-field boundary was raised in chapter 3 and from the results shown one must conclude that it is difficult to determine. From the measurements undertaken one can generalise that the attenuation with distance graphs become more predictable at frequencies above 5MHz and at distances beyond 8m but the standing wave patterns associated with the topology, geography and environment make it a difficult parameter to predict. On a calibrated OATS, one would take measurements of large signals and expect to see predictable curves, and perhaps the only way to estimate the near-field/far-field boundary would be at a very

rural individual premises. The value would of course be specific to the premises and therefore its utility would be minimal. In the absence of measurement one should therefore assume that all PLT measurements at the 1m or 3m distance are in the near-field and this could be extended to 10m on a conservative basis.

5.2.3 K-Factor Measurements

The difficulty in agreement of a CISPR 22 radiated standard gave rise to the concept of a K-Factor for premises that could be used to predict radiation based on a conducted emission test. With the radiated emission data gathered at the urban premises the K-Factor was calculated for each distance and frequency (paragraphs 4.9.2). This information was then presented in a number of formats to allow the comparison of K-Factor and different measurement distances, frequencies and injected voltages. The first conclusion to be drawn from the results is that there is a variation of up to 20dB/m at each frequency between a derived K-Factor measured at 1m compared to 10m. One can say with some certainty that K-Factor is frequency dependent but is affected greatly by injected power. This is mainly due to the dominance of the ambient noise at lower injected powers. One would expect the K-Factor with the 20V_{RMS} injected voltage to be more accurate than the 100mV_{RMS} injected power for that reason. It is however fundamentally derived from an in-situ measurement that is not well controlled and therefore one would expect a large variation in its value.

Investigation of the results measured in this research and that of others is that it offers little value. One could fix the measurement distance and procedure but fundamentally, like any antenna factor, it is specific to the premises under test, and is only valid at the measurement distance it was originated from. As it is derived from radiated emissions using a procedure which has already been shown to have errors of up to ± 15 dB its utility is questionable. It is therefore concluded that the benefit in determining the K-Factor of a premises is disproportionate to the effort involved in deriving it.

5.2.4 Actual PLT Effects

The conclusion of the paragraphs above is that to determine an acceptable limit either by prediction, modelling or even measurement is not going to provide an answer other than one that is very general because the effects of PLT on other services are not well understood. The purpose of the mutual interference tests (paragraph 4.8.3) was to determine the actual effect that PLT may have on a victim receiver. The conclusion was that PLT significantly affects victim receivers at distances up to 3m and thereafter the ability of the user to tolerate interference increases. At distances beyond 6m the PLT effects are largely ineffectual and therefore a decision should be taken on where a likely victim receiver in the HF band might have its antenna placed as opposed to where the victim receiver is. This is important because the most likely victims of PLT interference will be the amateur radio community and not others such as the military that have been discussed in the past.

Overall, the conclusion to be drawn from these measurements is that, due to the variability of techniques and the amount of error in the measurement, any relationship between radiated emission and the signal to noise ratio at the victim receiver is tenuous. If the standardisation bodies want to devise a test that accurately reflects the likely interference on a victim receiver in the near-field, using best practice from EMC radiated standards which all apply to the far-field, it will be of limited value. A better course of action would be to devise a radiated near-field test using an antenna that more accurately reflects the setup of the victim system. This may be a short whip antenna if it is to determine the effects of a small mobile HF radio or a large dipole at some agreed distance from the source. The process that has been undertaken in the previous 10 years has not delivered a standard and due to the variability in results, it is difficult to determine how this would change in the near future. Equally, interference only occurs if there is a victim and they are on the same frequency. A further

enhancement to the compliance of standards may be the use of a Monte-Carlo analysis of victims to the source of interference rather than just comparing radiated emissions to a protection requirement. Work undertaken in 2002 by CEPT (European Communications Office 2011) instigated this but it appears not to have been followed up.

The key aim of this research was to arrive at a “safe limit” for radiated emissions from PLT, however the previous chapters have demonstrated that this is a particularly difficult task. Chapter 6 will therefore briefly introduce some non-engineering factors that in the future may assist in the provision of an acceptable limit and concludes with a recommended way forward.

CHAPTER 6 - OTHER FACTORS, CONCLUSION AND FURTHER WORK

6.1 OTHER FACTORS

The previous chapters have explained the functionality that PLT can provide and the requirement for an agreed electromagnetic standard. They have further shown that the agreement of such a standard is highly complex and that although there are various methods such as theoretical prediction, modelling and measurement, there is significant variability of opinion within the standardisation bodies and researchers. This has often led to a polarised discussion of which methods are correct from an engineering perspective.

The agreement of an acceptable radiation limit however may not necessarily be derived from best engineering practice. From a strict EMC and engineering perspective PLT intentionally sends transients onto the power network, which for other appliances is always avoided. The transmission system is mismatched, causing an atypical amount of unwanted radiation for a communication system. The benefits of allowing PLT however may outweigh the effects on collocated systems (mainly intentional receivers) and therefore in coming to a decision of an acceptable limit other factors may have to be taken into consideration. This chapter discusses these factors, many of which are not related to engineering and assesses which factors have validity in determining the acceptable limit.

6.1.1 Political

During the run up to the UK 2010 general election the major political parties made commitments of increased broadband access to the nation to allow delivery of a range of services. Specifically, they wanted to address rural communities that currently have data rates less than 1Mb/s. In his first speech in office post the 2010 General Election

the UK Culture Secretary provided a speech (Hunt 2010) that set out the UK Coalition Government's policy (provided in full at Appendix I). The rationale that the UK place on an increased roll out of high speed broadband are mainly social and economic and are covered in the following paragraphs. In the UK it is expected that the roll out will be a range of fibre optic, wireless and PLT networks, with PLT being used primarily in rural areas for access and elsewhere in-house. The major EU countries are following suit and in the United States the Obama Administration has taken a similar line by agreeing the American Recovery and Reinvestment Act which will provide \$7.2 billion in loans and grants to expand broadband connections for residents of rural and underserved areas.

This has led to a response from the radio amateur community worldwide and specifically in the UK where the RSGB have set up a fund (RSGB 2010) to make a legal challenge to the communications regulator in the UK. This is a change in direction from opponents of PLT who have until recently always made the case for an acceptable limit on a strictly engineering basis. Similarly, the view of many EMC engineers is that there exists an EU directive, EU EMC standards and derived UK standardisation. These are explicit in their application; however other areas of the EU are encouraging the use of PLT. In reality many products have now gone to the market place and the belief is that whilst these may meet the conducted emission standard, they clearly radiate above a level that would normally be unacceptable. The concern of the EMC community is that if PLT does not have to comply with standards then the underlying notion of compliance becomes eroded. There is concern that if product manufacturers see a lack of enforcement of EMC standards, then they will use similar tactics to get other products to the market place. The costs of EMC design and testing can be substantial and increase both the price of the end product and affect industrial profits. It is therefore understandable that the EMC community see a threat to the credibility of their discipline and potentially to their existence.

6.1.2 Economic

The economic benefits of national high speed broadband fall into three main categories, namely revenue for governments, revenue for the communications industry through mass roll out and economic benefits to the user by having access to the internet.

As part of the recovery from recession caused by the banking crisis, governments are looking to cut back in public service employment and create more jobs in the manufacturing and service sector industries. An independent study (Council for Science and Technology 2010) has estimated that a government investment of £5bn would create nearly 300 000 jobs. For the government this means a reduction in welfare and benefits which is also a current pledge. The benefit to industry is therefore a large injection of revenue from the mass roll out of high speed broadband. There are also further benefits because companies that implement high speed broadband have tended to be more productive and have reduced overheads than those that have not embraced the technology. The companies rolling out broadband will be doing so in a climate of reduced public spending in a highly competitive market. The inclination will be for the lowest price initially rather than an expensive system that requires longer term payback. Under these constraints the roll out of PLT would become very attractive.

As well as high level cost benefits to governments and industry, the individual achieves benefit from being connected to the Internet. It is estimated that there are forty million internet users in the UK of which three quarters use it daily. It is, however, believed that there is a further quarter of the population that have never used the internet. The individual user now has access to a range of services that previously were only available by face to face transactions or by obtaining quotes from companies for

services. A range of comparison websites have grown up around the consumer market that allows simple queries to obtain the best prices from a range of manufactures. There are many examples but the ones that lead individuals to make the largest savings apply to purchases of large value items.

6.1.3 Social

The economic examples above demonstrate to the user the benefits of a fast and reliable connection to the Internet. There are other intangible benefits that can improve quality of life and again these can be delivered by governments, charities and provide a substantial improvement in quality of life to each member of society. From a government perspective they aspire to make as much information on public services available to as many individuals as possible. In the UK, the “Direct Gov” website provides information on employment and unemployment (benefits and job seeking), motoring (licensing, tax, testing), education and learning (grants, universities, schools), communities (housing, council taxation, flooding), crime and disabilities to name but a few. It could be argued that for those that do not have access to the internet and the one stop shop provided by “direct gov”, finding services is becoming more difficult. It is estimated (Hunt 2010) that four million adults in the UK do not have access to these facilities and rely on knowledge of each service individually to obtain social benefit. The management of these services can also be implemented more cost effectively over the internet rather than with public sector staff.

A very obvious social example is the proliferation of social networking sites such as “Facebook”. Individuals who find it difficult to socialise either through illness, disability, family constraints or other social issues can be connected to a wide range of new friends and activity groups. This has lead to an expansion in reach of the concept of a global network of friends unlimited by geographic constraints. There are also gaming

sites where societies are set up that work and operate together to undertake mutually beneficial tasks such as earning credits of some sort or fighting a common enemy.

Academically, The Open University in the UK provides materials on-line, allows foundation level assessments to be marked and returned on-line and provides live tuition using conferencing packages such as "Flash Meeting", "Lyceum", and "Illuminate". This particularly benefits students that cannot commit to a full time university degree or are constrained at home through illness, disability or other social difficulties.

As seen above, the social benefits are numerous and the potential for further enhancements such as on-line medical check-ups are on the horizon. These benefits require a reliable connection to the Internet and, as previously mentioned, certain areas will probably only ever receive high speed broadband over PLT unless a mass rollout of fast telecommunications networks take place in rural societies. It is for this reason that there is a strong political will by governments to find a solution that may not be based on best engineering practice but on other factors.

6.1.4 Subtle changes in regulation

When high speed PLT was first being considered, regulatory bodies appeared to be taking a hard line on equipment that interfered with or was expected to interfere with other services. In recent years, however, it would appear that existing laws are not being applied as rigorously as they previously may have been. The RSGB wrote to the EU commission asking for clarity in the interpretation of the application of the EMC directive recognising that there was a perceived economic benefit for EU economies. In the response (Verheugen 2009) the European Commission recognised that standardisation bodies had not delivered the desired result but was confident that this would take place within two years. The first point of note is that the Commission stated

that *"It is important to understand that it is the networks which radiate radio waves, and not the PLT devices themselves"*. This implies that there will be no radiated measurement applied to whole networks as long as the devices themselves comply with the appropriate conducted standards. The second point of note is that the standards, when they are agreed, will possibly allow non-compliance in frequency bands not used for amateur radio. The commission stated *"the Commission is now confident that adequate standards will emerge within the next two years and will integrate the appropriate mitigation techniques recently developed by PLT manufacturers"*. The final important point from the response is that the Commission have directed national regulators to recognise the benefits of PLT before undertaking enforcement action (*"In 2005 the Commission issued a Recommendation (2005/292/EC)(2) to Member States to ensure transparent, proportionate and non-discriminatory conditions for the deployment of powerline communications systems, and removal of any inappropriate regulatory barriers"*).

The view of the Commission is that market surveys have been undertaken, and, in a rollout of over ten million devices in the EU there have been limited claims of interference. The majority have been in the UK and these have been attributed in part to an active campaign by the RSGB to identify and report them to OfCom. The direction above to member states has led to OfCom being criticised by the radio community for not applying existing UK laws when a claim of interference is brought. OfCom in an attempt to retain political independence have commissioned an independent report (PA Consulting for OfCom 2010). It concludes that a proliferation of PLT devices onto the market that are compliant with current EMC standards would cause an increased number of cases of interference to radio amateurs. It does however note that mitigation techniques are in the process of being implemented in the next generation of PLT device which will reduce the number of incidents to an acceptable level. The report states: *"Our results indicate that the introduction of these features will be enough to*

reduce interference to negligible levels in the majority of cases. The exception to this is the safety critical aeronautical bands which we recommend are notched by default rather than by smart notching". The FCC in the US have taken a similar approach, but lost a court case to the ARRL in 2008 and have since made no overt change in position when compared with that of the EU.

6.1.5 Mitigation

In previous paragraphs the notion of mitigation techniques arose that could be allowed in the determination of compliance and enforcement. Notching has been briefly mentioned in previous chapters but in recent months it appears to be the mediator between those that are in favour of PLT and those that are not. It is therefore worthwhile discussing some of the technologies and their potential success in relation to licensing of PLT. There are various mitigation techniques that can be used of which some have been implemented in the past and others have potential future applications. The following paragraphs detail these techniques and refer to analysis by others on the protection that they may offer. Notching is well publicised in the PLT community and there are various techniques that can be used.

Firstly, rudimentary band notching was discussed in Chapter 2 in relation to a trial installation of prototype equipment in Crieff. If the frequencies of interest are known, whole sections of the available bandwidth can be notched by variable amounts of attenuation. Figure 6-1¹⁰ shows the current ITU frequency bands that should be protected.

¹⁰ - Courtesy of ITU

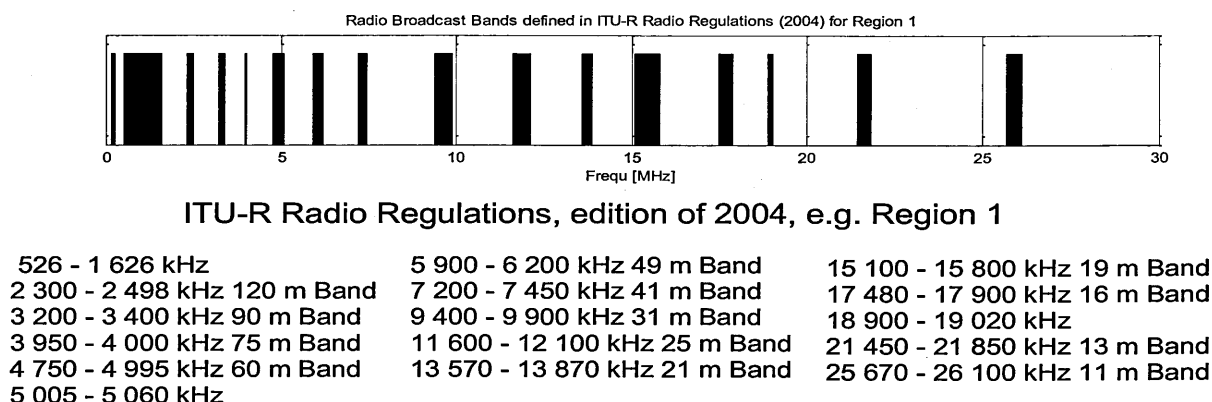


Figure 6-1 – ITU-R radio bands

Typical values have been 20dB and 40dB, but it should be noted that the more attenuation that is applied, the wider the notch becomes as the roll off at the edges of the bands does not take place over a few hertz but over kHz. As the bandwidth is limited by regulation, two factors make this less attractive. Firstly, many PLT devices use spread spectrum techniques such as DSSS and OFDM which therefore require large portions of bandwidth to keep the power levels low enough to meet compliance standards. As notches are implemented they constrain the available bandwidth, leading to a lower data rate and lower level of service to the consumer. Secondly, notches have to be applied at known frequencies irrespective of whether there is a victim receiver in the geographical location or not. In areas of dense population the implemented notches may have to increase and therefore the corresponding available bandwidth and data rate is reduced. Basic notching is relatively straightforward to implement but, as explained above, potentially reduces the available bandwidth to the consumer (estimated at 20% for most scenarios based on ITU allocations).

The second technique which has been trialled and is currently being further researched is adaptive notching (also known as smart notching). As its name suggests, it adaptively creates notches in the bandwidth based on the signal to noise ratio of the

PLT network itself. Monitoring circuits in the PLT modem detect known signals from within its own network and across the PLT spectrum and produce a table of signal to noise ratios. The underlying assumption is that ingress from radio transmissions causes noise on the network which can be correlated to transmissions in the amateur bands. Notches are then applied to where radio transmissions actually occur at the present time, rather than notching out entire bands whether transmissions are taking place or not. A secondary benefit is derived because, by applying PLT signals at frequencies of low signal to noise ratio, the data rate increases for the network provider due to a reduction in the bit error rate compared with basic notching. Results of initial tests (PA Consulting for OfCom 2010) have demonstrated that adaptive notching offers an improved level of protection in the HF band compared with standard Homeplug PLT devices and improved data rate for the PLT subscriber. It should be noted, however, that tests were conducted using high power commercial transmitters which significantly ingress onto the mains network and therefore the signal to noise ratio can be calculated by the adaptive detection circuits. For one to one global amateur communications, where signals are often around the noise floor and, in the case of communication intelligence (COMINT) systems which detect signals within the noise floor, adaptive techniques may not sufficiently mitigate the risk. Although ETSI are working on standardisation, the technique is currently proprietary to Sony and its mass roll out may be limited with intellectual property associated with its design, although there may be licensing options that other PLT manufacturers could investigate. Secondly the EMC testing of such devices would most likely be problematic as accurate and standardised radiated emission measurements of static sources are already difficult and therefore a new technique would have to be developed. This would require the development of a new standard and CISPR/CENELEC have demonstrated over the previous 10 years that this in itself has caused some difficulty.

An alternative mitigation strategy is to modify the power levels being transmitted by PLT modems to minimise co-site interference. Earlier modems had a fixed power output that was initially adjusted (including a margin for increased signal to noise ratio) based on the mains impedance that it had to overcome to communicate with other modems on the network. As the mains impedance is dynamic the signal to noise ratio and the bit error rate are variable. Modem manufacturers are now producing modems that allow the transmitted power to be adjusted automatically based on the channel conditions in real time. This could allow the modem to be adjusted down to the minimum transmit power to allow reliable transmission and provide an element of protection to co-site receivers. A complementary strategy would be to also determine what an acceptable bit error rate would be for a specific data transfer rather than operating at the optimum or agreed standard. For example, if a PLT provides a 50MB/s data rate as part of its agreed specification then it will adapt its power levels as discussed to attempt to maintain this for different channel conditions. If the user is only transferring basic files, e-mails or web browsing rather than streaming video then the required data rate may be as low as 1MB/s. By adaptively reducing the transmit power to a lesser level than above, the bit error rate would increase. The increased bit error rate would then cause a reduction in data rate but this reduction may be acceptable (and in fact could go unnoticed) to the user. Therefore an adaptive power management strategy should take account of the signal to noise ratio based on data ingress and also on the data rate required for the current task. In addition the aim of all PLT modems constructed in accordance with the Homeplug standards should be to transmit the minimum power levels during idle periods.

In summary, there are various mitigation methods in the power, frequency and time domains that can be implemented that may allow coexistence. They are, however, mitigations to an underlying issue on the agreement of a standard and until the technologies mature they should be continually reviewed in order not to lose sight of

the underlying EMC issue. Figure 6-2¹¹ shows the expected in-service dates of some of these mitigation techniques.

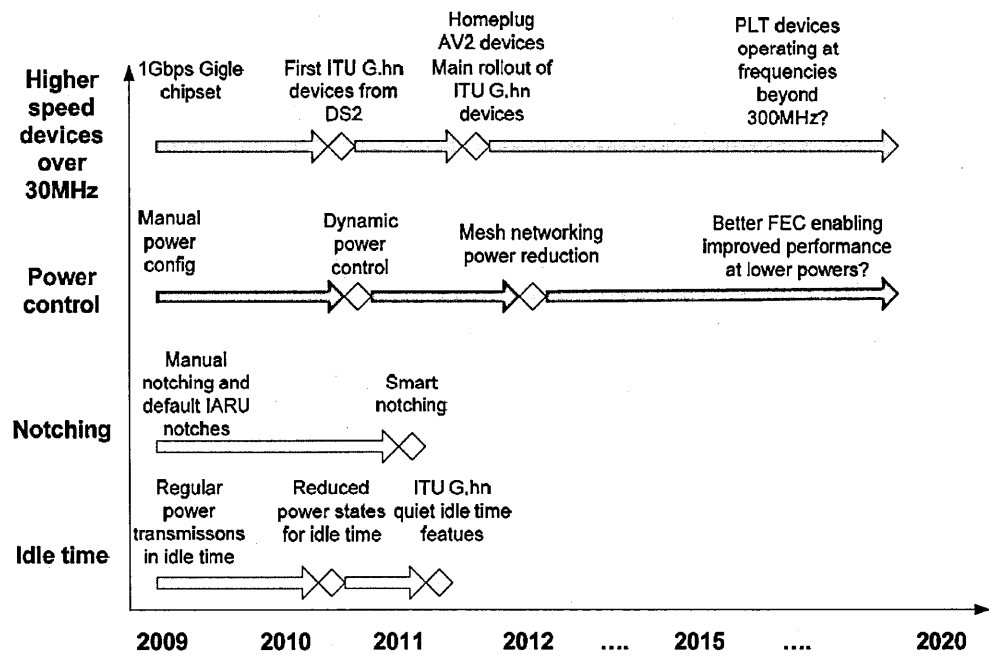


Figure 6-2 – Predicted PLT modem future roadmap

6.1.6 Future Factors

Although mitigation may offer a way forward for regulators to meet government objectives, the debate continues primarily between the radio amateur community and supporters of PLT (industry and government). Apart from the current political, social and economic factors discussed, there are also other future factors that at first sight may not appear obvious but could give an insight into a resolution to the issue.

The debate so far has argued that there are alternatives to access PLT systems such as cable, fibre and xDSL. There are also alternatives to in-house PLT systems such as Wi-Fi or hidden Ethernet networks in new build houses. Those opposed to PLT would rightly argue that PLT is not the most optimum delivery method and that whilst alternatives exist it would make sense to pursue those. There is, however, a new potential requirement that currently has no obvious competition and that is the future

¹¹ - Courtesy of OfCom

smart grid. The smart grid allows the utility companies to send information around their networks on the status of each user and delivery of electricity and gas. The first benefit is that the utility companies can remotely read the meters of users without having to send a meter reader to the premises. This has an obvious financial benefit to the utility companies but it is limited because currently the user can call through meter readings by telephone. It is implemented currently using the low frequency standards but in the future the data rate required is likely to be increased due to smart metering. Utility companies are in the process of rolling out smart meters to consumers that will allow them to monitor real time energy consumption and adapt their lifestyles accordingly. For example the current devices have a "traffic light" system and a more detailed menu system that highlights the current use and cost per use at any point in time. When a user switches on a high power appliance such as a heater, kettle, iron or electric oven, the meter would change from green to amber or red. Equally, during the night, a consumer can determine how much residual energy is being consumed by appliances on standby or phone and games chargers. The same can be applied to the gas supply.

This level of information provision to the consumer is seen by the utility companies and governments as being the key to protecting dwindling natural resources. There is a fear that the provision of natural gas by other countries, the lack of support for nuclear generation and the decrease in the use of fuel means that consumption must reduce. Overlaid to this is the commitments made by each government as part of the United Nations Framework Convention on Climate Change (UNFCCC 1998) to reduce greenhouse emissions. To reduce emissions, part of the solution will be less consumption controlled by the user, which in part provides natural protection, security and resilience of those supplies.

User control is seen as only the start of the smart grid. The next phase would see information being collected dynamically by utility companies and balancing their

provision to actual demand. When each household and business sends information of consumption back in real time, the data requirements of the network start to become larger than the low frequency standard can accommodate. The long term future could see smart appliances such as washing machines and dishwashers being programmed to be "ready to go" and the utility company could control when it could be operated such as through the night or at other non-peak times. For this inconvenience the consumer would be offered a reduced tariff because the utility company would have better control of the supply. It is therefore clear that PLT could deliver real strategic government objectives and its support begins to dwarf the inconvenience of interference in the HF spectrum.

The other factor that may see a resolution to the problem would be a change in frequency band for PLT. Although, historically, development of PLT has been in the HF band some manufacturers are using frequencies up to 80MHz (into the VHF band) and some are investigating frequencies up to 300MHz which is into the UHF band. In some respects this is inevitable because data rate is inextricably linked to frequency bandwidth (as described by the Shannon-Hartley theorem) and the perceived increase in data requirements will lead PLT manufacturers above HF.

Whilst this could appease the radio amateur community it will cause the same effects to a different set of users. The main user of the VHF frequency spectrum is civilian air traffic control with a mass roll out of PLT in this band. It is possible that interference may not manifest itself because aircraft are generally kept apart from PLT installations by low flying regulations and perimeter protection of airfields. Many of the other users that traditionally used VHF (emergency services) have moved to higher bands to obtain secure communications and therefore the issues may not arise. If any of these services are affected the opposition would be far stronger than can be put forward by the Radio Amateur community and some of the mitigation techniques may have to be adopted in

a more strictly controlled manner leading to a reduction in data rate. Equally, the key reason for complaint by radio amateurs is because their receivers and antenna are collocated with PLT devices and results from chapter 4 show that separation by 100m would, under normal circumstances, reduce interference to a manageable level. In the VHF and UHF band the communications systems are more robust and collocation is not such an issue and therefore the reduction in interference caused by a move away from the HF band may be a convenient by-product of the search for higher data rates.

6.1.7 Conclusion.

It is apparent from the social and economic benefits that both governments and individuals benefit hugely from fast connections to the Internet. It is also clear that currently there are large areas that do not have access to fast broadband due to their location with respect to either telephone exchanges or access to cable networks. This is particularly the case in rural environments. Governments have identified this as a major political factor and have endeavoured to make changes to deliver fast broadband and have identified regulation as an area that appears to be inhibiting progress. The UK culture minister stated *"Our plan is to establish a series of rural market testing projects.....to understand what kind of government support will be necessary"*. He further stated *"we want to cut the costs of investing in superfast broadband networks by opening up access to the existing network of telecoms and utility companies.....[to understand] the kind of changes we could make to the legislative framework or what other kind of regulatory support we could provide"*.

By recognising this and observing how the regulatory bodies are taking a softer view on their approach to PLT, it is apparent that if an engineering solution is not agreed in the short term, a non-engineering solution may be considered. Rather than attempt to agree a compliance standard which has caused great difficulty in the previous 10 years, the proposed strategy is now to investigate mitigation through the use of adaptive temporal, frequency and power management techniques. This is a significant

change in direction away from traditional EMC compliance and enforcement to facilitate the roll out of high speed broadband. In the course of the next few years other factors such as a roll out of the smart grid will only add further pressure to the regulatory bodies to come to a formal conclusion on the licensing and regulation of PLT.

6.2 OVERALL CONCLUSION

PLT has the potential to be a useful method for delivering various types of data to consumers, particularly where broadband networks would not be rolled out using traditional methods, because market forces would make them uneconomical. Since the early 90s international, European and national regulatory bodies have attempted to derive an acceptable limit that would allow PLT to coexist with radio services. Even today the forward plan by CISPR to resolve this issue is very similar to its previous plans and a successful outcome is not guaranteed. The original aim of this research was to understand the difficulties that standardisation bodies such as CISPR faced and investigate alternative methods for coexistence.

Others have tried in the past, and chapter 2 critically analysed various studies into PLT that also attempted, to derive a “safe limit”. These studies fell into three categories:

- Those that used theoretical prediction
- Those that used modelling because there were no networks
- Those that made measurements

In reality, a PLT system, whether it is access or in-house, is inherently difficult to predict due to the variability of network conditions, geography and network topology. Maxwell's Equations as the underlying principle for all prediction and modelling, can only be accurately applied in systems of considerable symmetry or on models that have been simplified. This also applies to EMC measurements due to physical size, environmental factors and near and far-field uncertainty. These measurements are inaccurate compared to the standardised and repeatable measurements that would be

expected for EMC compliance. In almost all PLT predictions and measurements to date, the errors associated with these limitations have been simplified or ignored and consequently the credibility of the conclusions is a source of debate.

A component of this research was to assess these errors and apply them to actual measurements to determine how critical errors were to the end result and to come up with a “safe limit” but noting an area of uncertainty. The key area to be addressed was the attenuation of PLT emissions with distance and to determine their affects on radio services using mutual interference testing. This concluded that attenuation with distance of 10-20dB/decade is typical for the HF band up to a distance of 20m due to near-field factors. With limited PLT networks to undertake further testing on and the pace of change of new PLT devices to the market, it is difficult to generalise the interference effects as manufactures were and are still rolling out new and innovative protocols and frequency management solutions to accommodate notching and adaptive power.

Whilst the ideal solution to the coexistence problem would be a robustly estimated engineering based approach, there are other factors that may lead to a solution. In recent years political, social and economic factors have escalated the profile of PLT to become part of strategic government policy which will affect the acceptable emission limits that are finally agreed.

6.3 FURTHER WORK

Work to date has concentrated on measuring PLT radiated emissions at limited field trials. Globally, the last significant measurements were taken in Scotland in 2005 and since then there have been no significant PLT networks deployed. In that time in-house solutions have been purchased by consumers but their location and distribution is largely unknown. As adaptive notching and power management are the likely solutions

to the coexistence problem, a large scale trial with effects on radio services should be implemented. It is recognised that this will require industrial support and that it may have to be a joint industry and government partnership for financial reasons. The aim would be to determine the cumulative effects of a significant roll out of a dynamically controlled network and estimate a safe distance from modems to victim receivers.

The conclusion from this thesis is that a “safe limit” does not exist and it will always be a compromise between user data rate requirements, low noise environments for radio amateurs and the integrity of the EMC measurement process. This compromise is now being arbitrated by governments who have more strategic agendas and are less interested in sound engineering judgement and are now progressing towards an “acceptable limit”. Recognising this, it is probably now time to set an arbitrary conducted emission limit and mandate certain mitigation techniques because, at present, devices are getting to the market effectively unregulated. It is estimated that in the UK there are 1.5 million devices in use, and complaints so far have been limited to around 250 (PA Consulting for OfCom 2010). Such a limit should be agreed in CISPR 22 and a limit of 50-60dB μ V/m using a quasi-peak detector appears to be a fair compromise for the unnotched portions before power management techniques are implemented. This would be beneficial to the industry that is nervous about rolling out networks with no clear regulatory direction. This would, however, need to be offset by a system for reasonable complaints, which to date has been equally constrained by process. The actual measurement technique and distance may no longer be particularly important because a subjective and realistic assessment can be made. A known data set can be sent around a network to confirm the source of interference. The resolution of the conflict should then be a joint venture between the PLT consumer and the plaintiff. Possible solutions may be deeper notches, lower power and lesser data for the consumer. There also needs to be reasonable solutions by the plaintiff

such as relocating antennas or using different techniques, frequencies and procedures.

EMC is after all about mutual compatibility.

**APPENDIX A: RADIATED EMISSIONS, BRADLEY STOKE, ANTENNA
PARALLEL, AMBIENT SUBTRACTED, 20V INJECTED**

The following measurements were taken on the 6th – 21st of January 2005 in Bradley Stoke, Bristol for a 20V injected signal. The antenna was oriented parallel to the premises and was positioned at various distances from the front of the premises. For each table, the measurement distance is tabulated alongside the frequency the measurement was taken at and the measured value in dBµV/m and its corresponding value in V/m.

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	1.6	69.5	0.002985383
1.5	1.6	64.5	0.001678804
2	1.6	72.5	0.004216965
2.5	1.6	68.5	0.002660725
3	1.6	67.5	0.002371374
3.5	1.6	68.5	0.002660725
4	1.6	65.5	0.001883649
4.5	1.6	65.5	0.001883649
5	1.6	64.5	0.001678804
6	1.6	63.5	0.001496236
7	1.6	62.5	0.001333521
8	1.6	60.5	0.001059254
9	1.6	60.5	0.001059254
10	1.6	54.5	0.000530884

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	5	83.5	0.014962357
1.5	5	79.5	0.009440609
2	5	75.5	0.005956621
2.5	5	73.5	0.004731513
3	5	69.5	0.002985383
3.5	5	67.5	0.002371374
4	5	65.5	0.001883649
4.5	5	63.5	0.001496236
5	5	64.5	0.001678804
6	5	66.5	0.002113489
7	5	55.5	0.000595662
8	5	52.5	0.000421697
9	5	62.5	0.001333521
10	5	52.5	0.000421697

Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	10	73.5	0.004731513
1.5	10	71.5	0.003758374
2	10	71.5	0.003758374
2.5	10	71.5	0.003758374
3	10	69.5	0.002985383
3.5	10	67.5	0.002371374
4	10	64.5	0.001678804
4.5	10	63.5	0.001496236
5	10	62.5	0.001333521
6	10	60.5	0.001059254
7	10	51.5	0.000375837
8	10	54.5	0.000530884
9	10	62.5	0.001333521
10	10	59.5	0.000944061

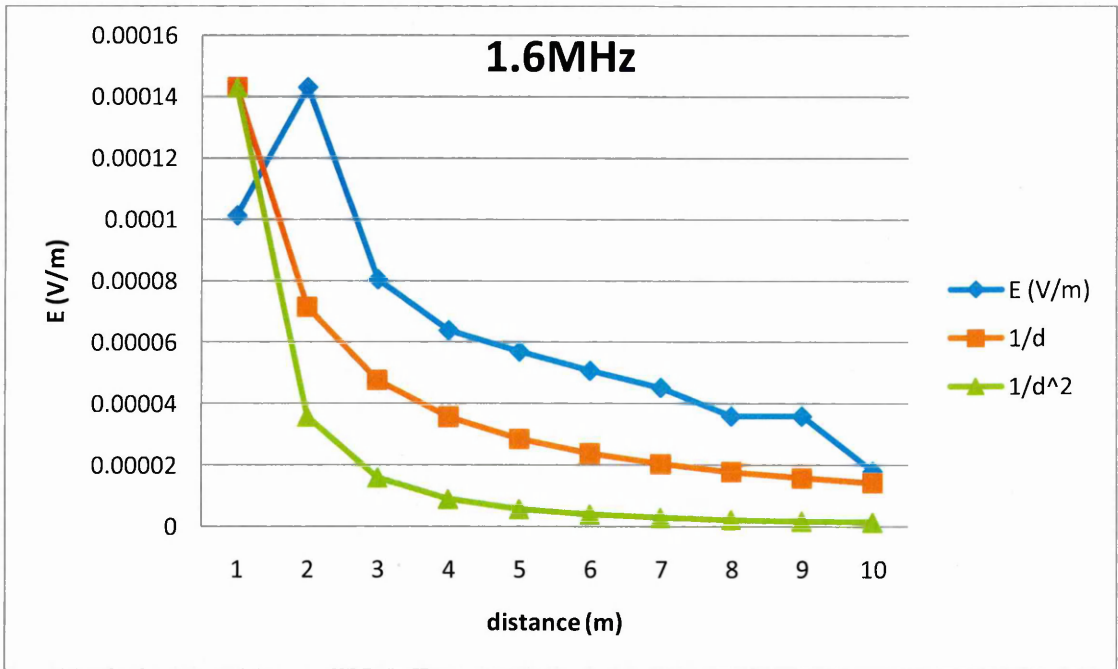
Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	15	72.5	0.004216965
1.5	15	71.5	0.003758374
2	15	67.5	0.002371374
2.5	15	69.5	0.002985383
3	15	68.5	0.002660725
3.5	15	65.5	0.001883649
4	15	61.5	0.001188502
4.5	15	54.5	0.000530884
5	15	57.5	0.000749894
6	15	55.5	0.000595662
7	15	62.5	0.001333521
8	15	60.5	0.001059254
9	15	72.5	0.004216965
10	15	65.5	0.001883649

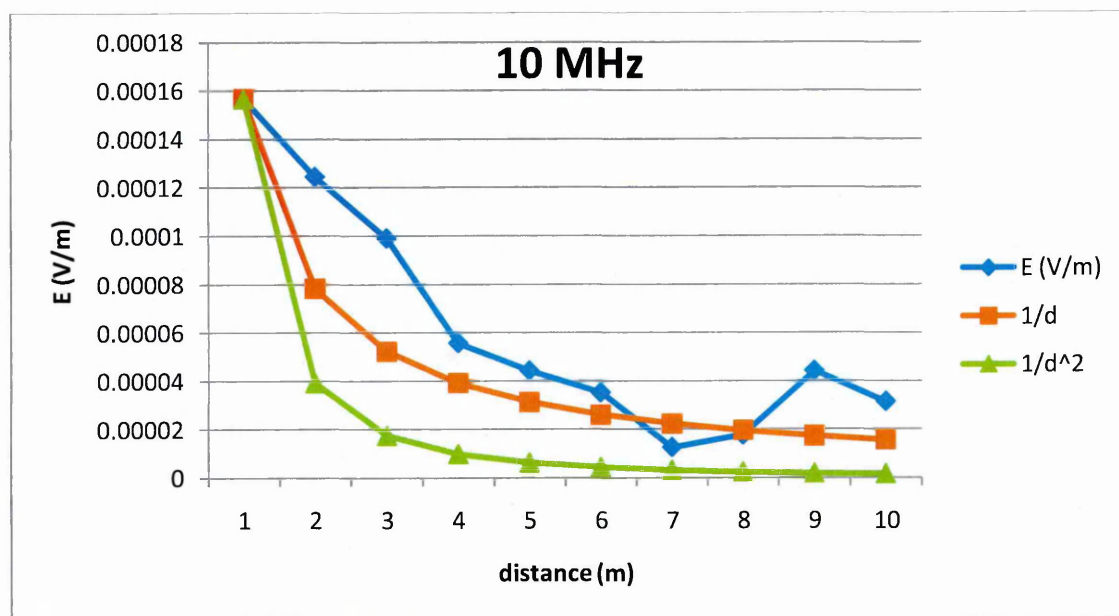
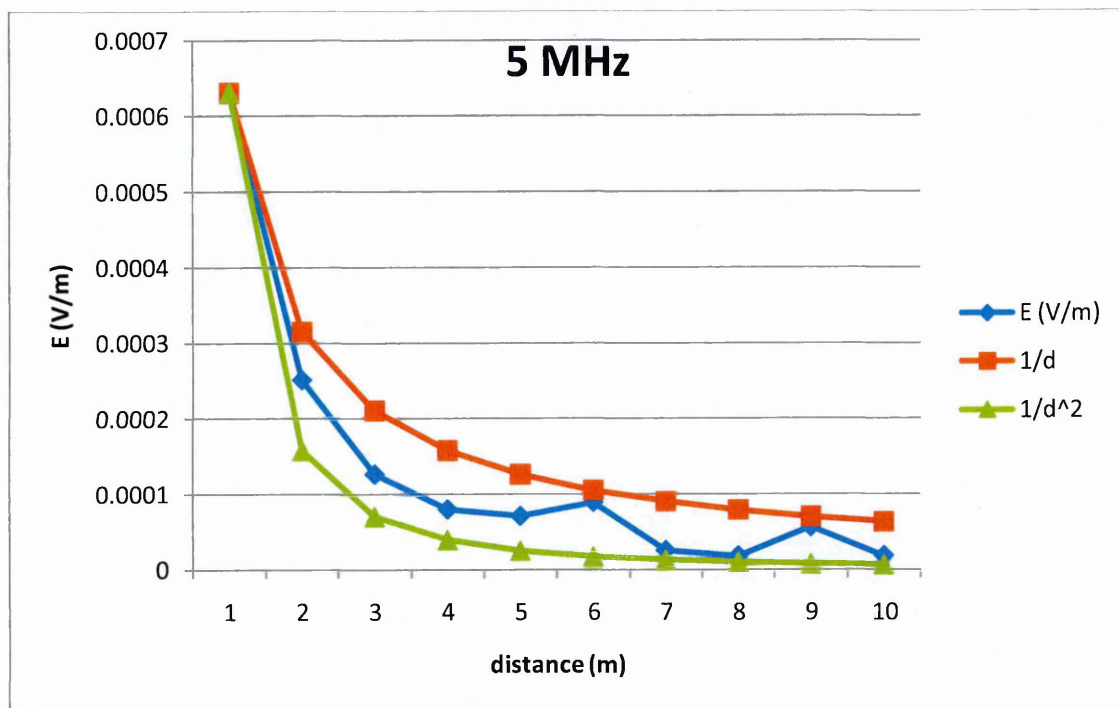
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	20	87.5	0.023713737
1.5	20	84.5	0.01678804
2	20	84.5	0.01678804
2.5	20	82.5	0.013335214
3	20	82.5	0.013335214
3.5	20	80.5	0.010592537
4	20	80.5	0.010592537
4.5	20	80.5	0.010592537
5	20	79.5	0.009440609
6	20	78.5	0.008413951
7	20	79.5	0.009440609
8	20	76.5	0.006683439
9	20	73.5	0.004731513
10	20	57.5	0.000749894

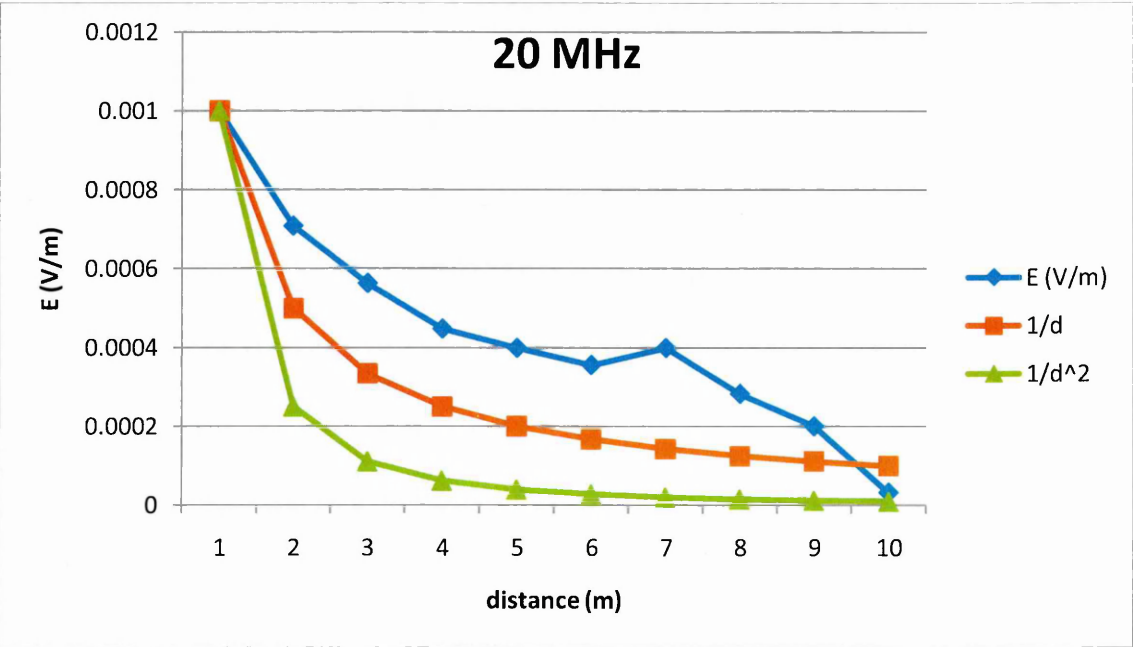
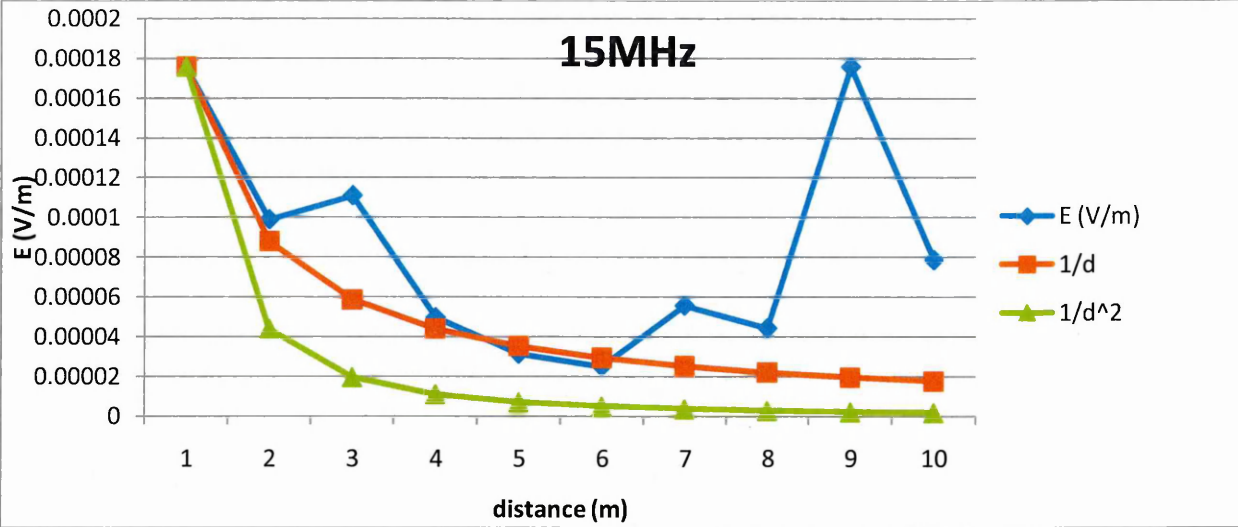
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	25	82.5	0.013335214
1.5	25	76.5	0.006683439
2	25	73.5	0.004731513
2.5	25	69.5	0.002985383
3	25	67.5	0.002371374
3.5	25	66.5	0.002113489
4	25	65.5	0.001883649
4.5	25	64.5	0.001678804
5	25	62.5	0.001333521
6	25	57.5	0.000749894
7	25	62.5	0.001333521
8	25	61.5	0.001188502
9	25	65.5	0.001883649
10	25	65.5	0.001883649

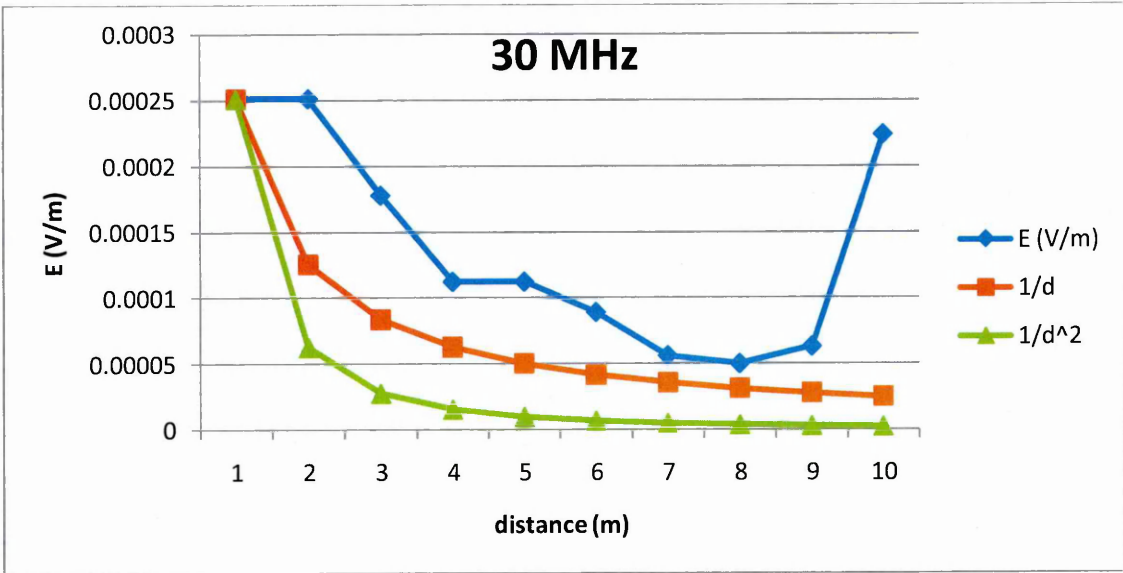
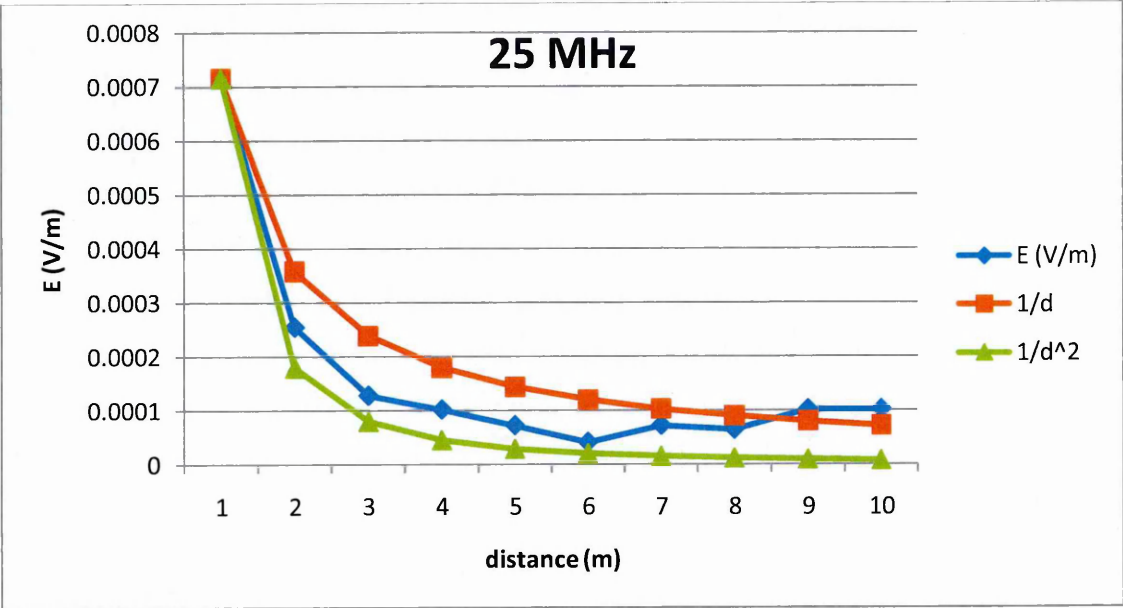
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	30	73.5	0.004731513
1.5	30	68.5	0.002660725
2	30	73.5	0.004731513
2.5	30	71.5	0.003758374
3	30	70.5	0.003349654
3.5	30	67.5	0.002371374
4	30	66.5	0.002113489
4.5	30	65.5	0.001883649
5	30	66.5	0.002113489
6	30	64.5	0.001678804
7	30	60.5	0.001059254
8	30	59.5	0.000944061
9	30	61.5	0.001188502
10	30	72.5	0.004216965

The following graphs are those that have been plotted from each table above with the ambient noise subtracted.









**APPENDIX B: RADIATED EMISSIONS, BRADLEY STOKE, VECTOR SUM,
AMBIENT SUBTRACTED, 20V INJECTED**

The following measurements were taken on the 6th – 21st of January 2005 in Bradley Stoke, Bristol. The antenna was oriented parallel and perpendicular to the premises and was positioned at various distances from the front of the premises. The results are the vector summation of both orientations. The detail of each column is the same as Appendix A.

Distance (m)	Frequency (MHz)	E (V/m) Perp	E (V/m)	E (V/m) Vector
1	1.6	0.00012735	0.002985383	0.002988098
2	1.6	0.00012735	0.004216965	0.004218888
3	1.6	9.01571E-05	0.002371374	0.002373087
4	1.6	8.03526E-05	0.001883649	0.001885362
5	1.6	6.38263E-05	0.001678804	0.001680017
6	1.6	5.06991E-05	0.001496236	0.001497095
7	1.6	3.1989E-05	0.001333521	0.001333905
8	1.6	2.54097E-05	0.001059254	0.001059559
9	1.6	9.01571E-06	0.001059254	0.001059292
10	1.6	6.38263E-06	0.000530884	0.000530922

Distance (m)	Frequency (MHz)	E (V/m) Perp	E (V/m)	E (V/m) Vector
1	5	0.000199526	0.014962357	0.014963687
2	5	0.000158489	0.005956621	0.005958729
3	5	0.000112202	0.002985383	0.002987491
4	5	0.0001	0.001883649	0.001886302
5	5	7.94328E-05	0.001678804	0.001680682
6	5	5.01187E-05	0.002113489	0.002114083
7	5	7.07946E-05	0.000595662	0.000599854
8	5	5.01187E-05	0.000421697	0.000424665
9	5	0.0001	0.001333521	0.001337265
10	5	5.62341E-05	0.000421697	0.00042543

Distance (m)	Frequency (MHz)	E (V/m) Perp	E (V/m)	E (V/m) Vector
1	10	8.81049E-05	0.004731513	0.004732333
2	10	0.000139637	0.003758374	0.003760967
3	10	0.000139637	0.002985383	0.002988647
4	10	0.000124451	0.001678804	0.001683411
5	10	0.000110917	0.001333521	0.001338126
6	10	8.81049E-05	0.001059254	0.001062912
7	10	4.4157E-05	0.000375837	0.000378422
8	10	6.23735E-05	0.000530884	0.000534536
9	10	8.81049E-05	0.001333521	0.001336428
10	10	4.9545E-05	0.000944061	0.00094536

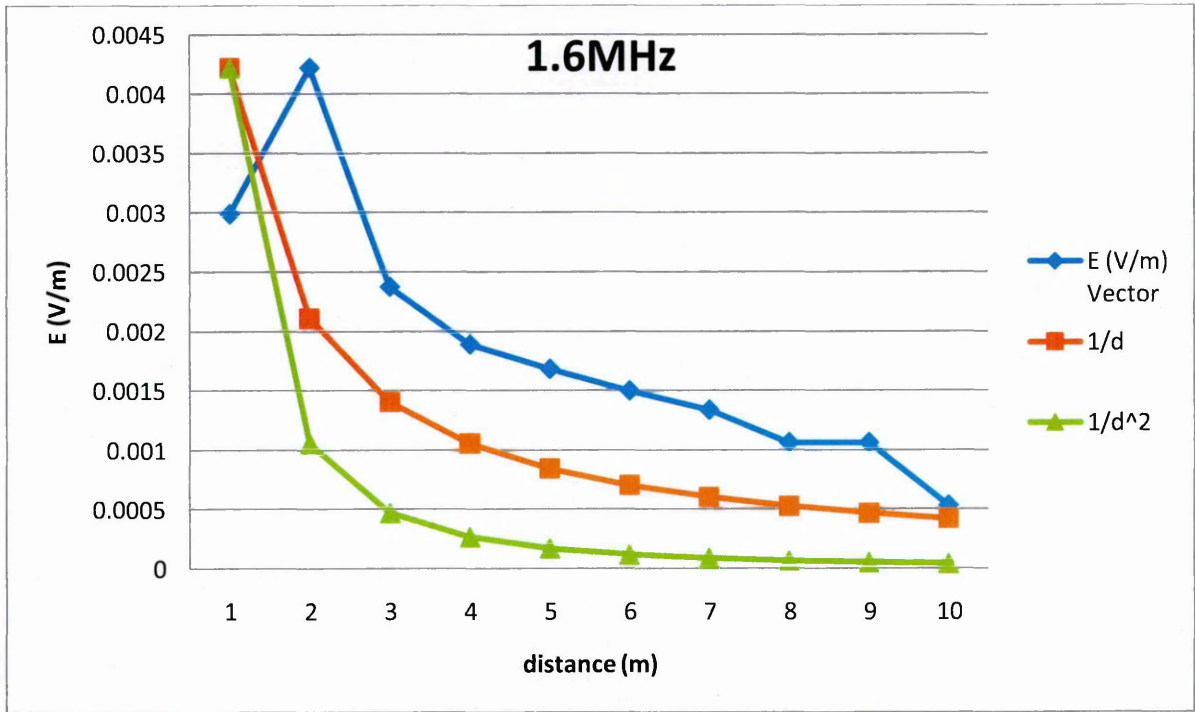
Distance (m)	Frequency (MHz)	E (V/m) Perp	E (V/m)	E (V/m) Vector
1	15	0.000350752	0.004216965	0.004231527
2	15	0.000175792	0.002371374	0.002377881
3	15	0.000248313	0.002660725	0.002672287
4	15	0.000248313	0.001188502	0.001214165
5	15	0.000248313	0.000749894	0.000789937
6	15	0.000248313	0.000595662	0.000645347
7	15	0.000124451	0.001333521	0.001339316
8	15	0.000221309	0.001059254	0.001082126
9	15	0.00049545	0.004216965	0.00424597
10	15	0.000278612	0.001883649	0.001904142

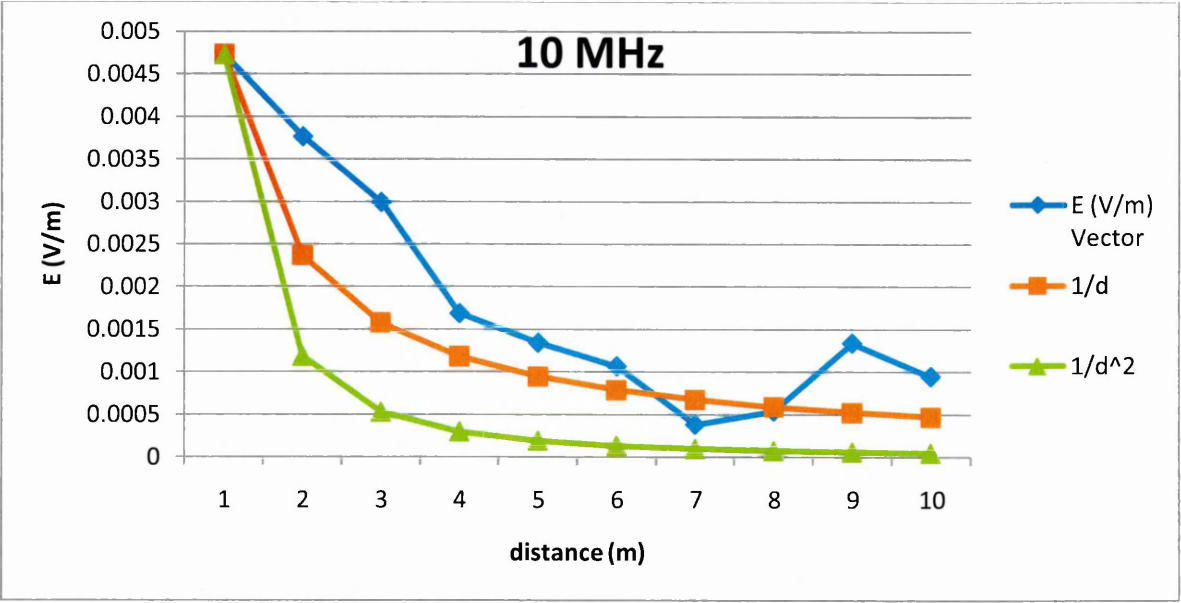
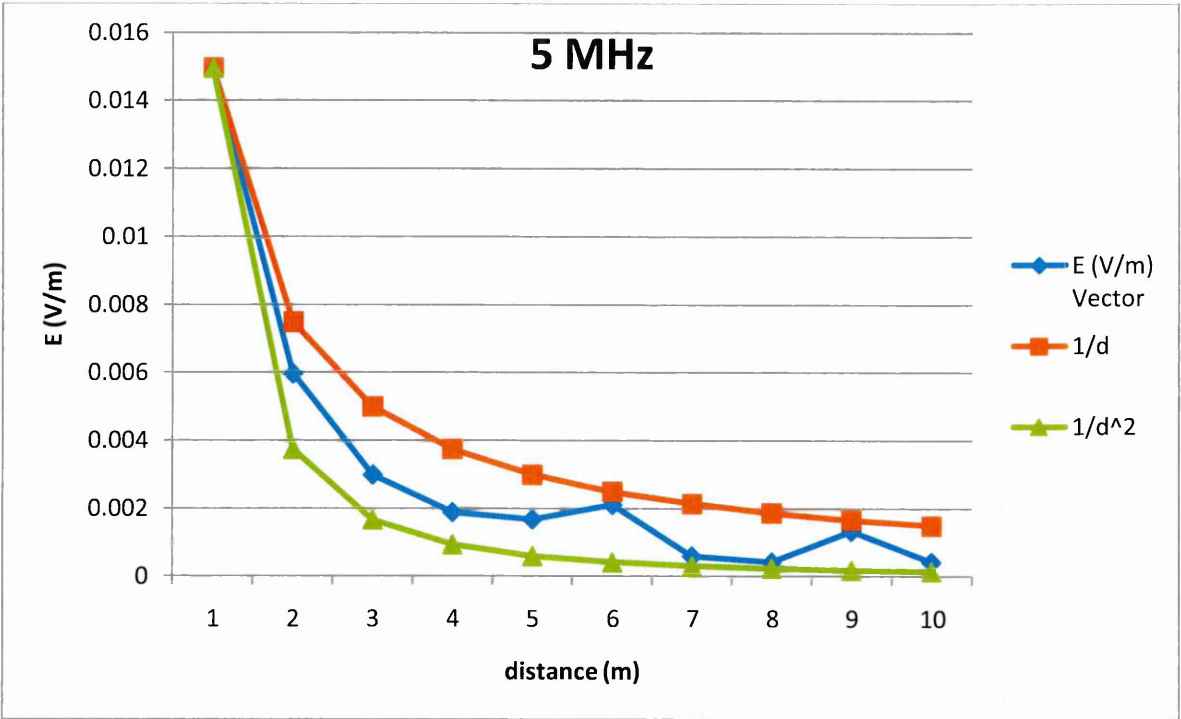
Distance (m)	Frequency (MHz)	E (V/m) Perp	E (V/m)	E (V/m) Vector
1	20	0.000354813	0.023713737	0.023716391
2	20	0.000562341	0.01678804	0.016797456
3	20	0.000630957	0.013335214	0.013350133
4	20	0.000794328	0.010592537	0.010622278
5	20	0.000707946	0.009440609	0.009467116
6	20	0.000707946	0.008413951	0.008443682
7	20	0.000316228	0.009440609	0.009445904
8	20	0.000501187	0.006683439	0.006702205
9	20	0.000281838	0.004731513	0.0047399
10	20	0.000177828	0.000749894	0.00077069

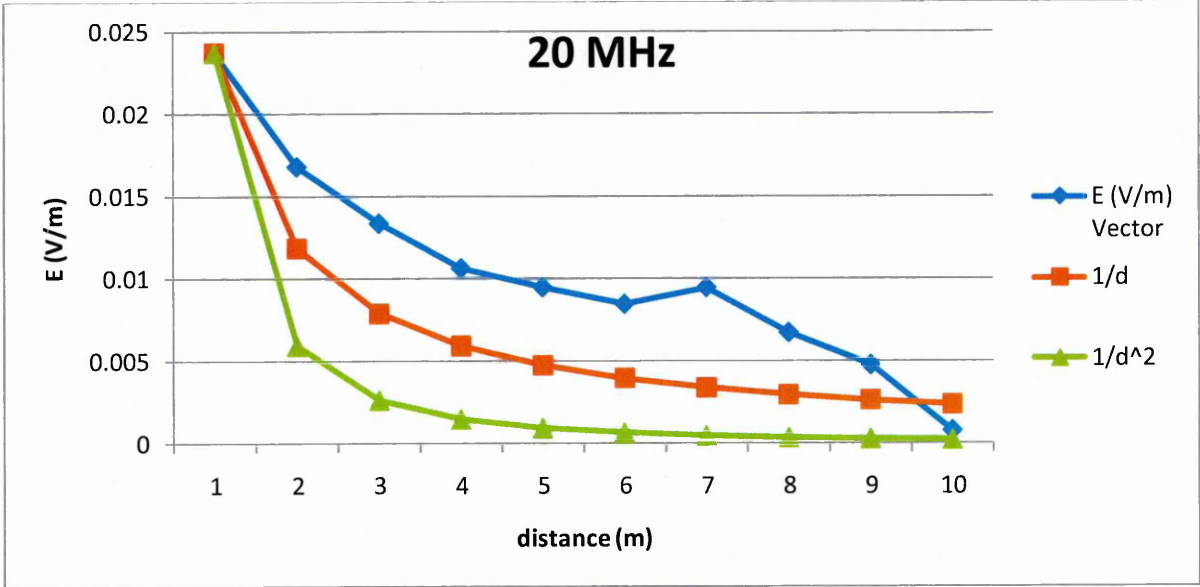
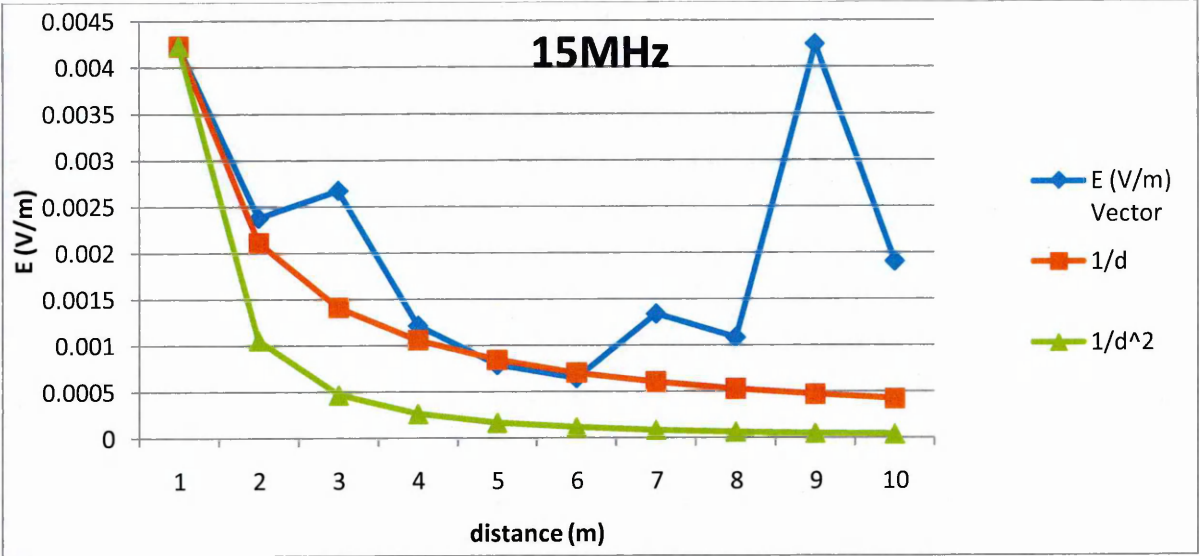
Distance (m)	Frequency (MHz)	E (V/m) Perp	E (V/m)	E (V/m) Vector
1	25	0.000254097	0.013335214	0.013337635
2	25	0.000142889	0.004731513	0.00473367
3	25	7.16143E-05	0.002371374	0.002372455
4	25	9.01571E-05	0.001883649	0.001885805
5	25	0.00012735	0.001333521	0.001339588
6	25	0.000113501	0.000749894	0.000758435
7	25	0.000142889	0.001333521	0.001341155
8	25	0.000179887	0.001188502	0.001202038
9	25	0.000113501	0.001883649	0.001887065
10	25	7.16143E-05	0.001883649	0.00188501

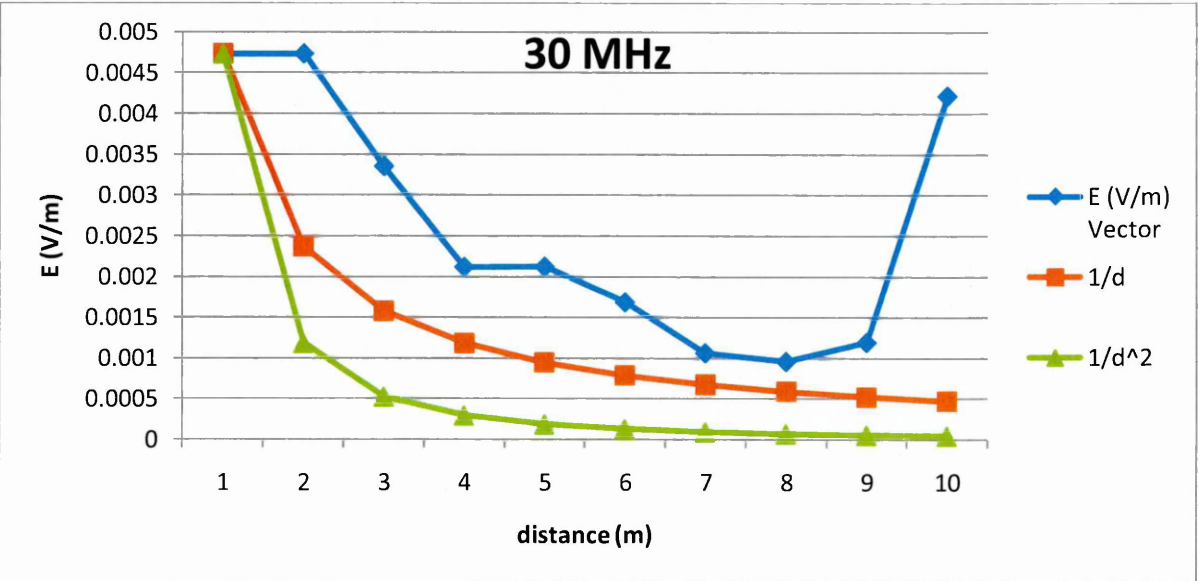
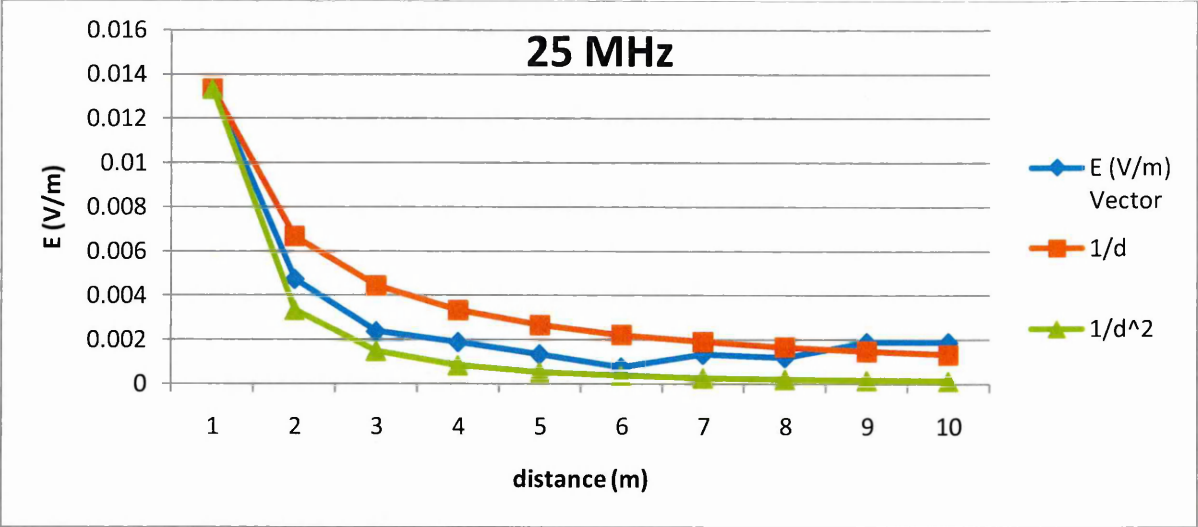
Distance (m)	Frequency (MHz)	E (V/m) Perp	E (V/m)	E (V/m) Vector
1	30	0.000112202	0.004731513	0.004732843
2	30	0.000125893	0.004731513	0.004733188
3	30	0.000112202	0.003349654	0.003351533
4	30	0.000112202	0.002113489	0.002116465
5	30	0.000177828	0.002113489	0.002120957
6	30	0.000158489	0.001678804	0.001686269
7	30	7.94328E-05	0.001059254	0.001062228
8	30	0.000158489	0.000944061	0.000957272
9	30	0.000112202	0.001188502	0.001193787
10	30	7.94328E-05	0.004216965	0.004217713

The following graphs are those that have been plotted from each table above with the ambient noise subtracted.









APPENDIX C: RADIATED EMISSIONS, BRADLEY STOKE, ANTENNA

PERPENDICULAR, AMBIENT SUBTRACTED, 100mV INJECTED

The following measurements were taken on the 6th – 21st of January 2005 in

Bradley Stoke, Bristol with an injected voltage of 100mV. The antenna was oriented perpendicular to the premises and was positioned at various distances from the front of the premises. The columns are the same as in Appendix A.

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	1.6	14.2	5.12861E-06
2	1.6	14.4	5.24807E-06
3	1.6	11.3	3.67282E-06
4	1.6	9	2.81838E-06
5	1.6	9.3	2.91743E-06
6	1.6	7.9	2.48313E-06
7	1.6	6.3	2.06538E-06
8	1.6	5.3	1.84077E-06
9	1.6	3.8	1.54882E-06
10	1.6	3.1	1.42889E-06

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	5	24.5	1.6788E-05
2	5	21.7	1.21619E-05
3	5	19.7	9.66051E-06
4	5	17.7	7.67361E-06
5	5	15.9	6.23735E-06
6	5	14.5	5.30884E-06
7	5	13.8	4.89779E-06
8	5	13.4	4.67735E-06
9	5	11.4	3.71535E-06
10	5	19.1	9.01571E-06

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	10	18.1	8.03526E-06
2	10	18.2	8.12831E-06
3	10	18.4	8.31764E-06
4	10	17.3	7.32825E-06
5	10	15.3	5.82103E-06
6	10	13.2	4.57088E-06
7	10	12.8	4.36516E-06
8	10	13.3	4.62381E-06
9	10	14.3	5.188E-06
10	10	14.1	5.06991E-06

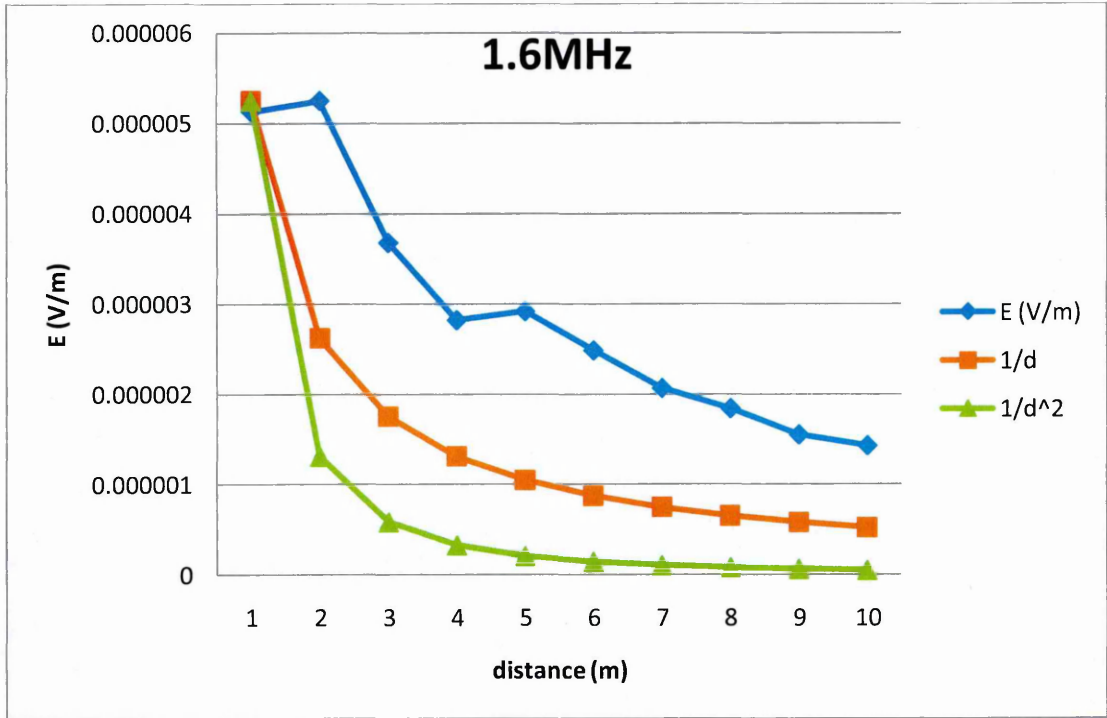
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	15	20	0.00001
2	15	17.5	7.49894E-06
3	15	11.3	3.67282E-06
4	15	15	5.62341E-06
5	15	16.9	6.99842E-06
6	15	14.8	5.49541E-06
7	15	12.8	4.36516E-06
8	15	11.6	3.80189E-06
9	15	18.6	8.51138E-06
10	15	18.2	8.12831E-06

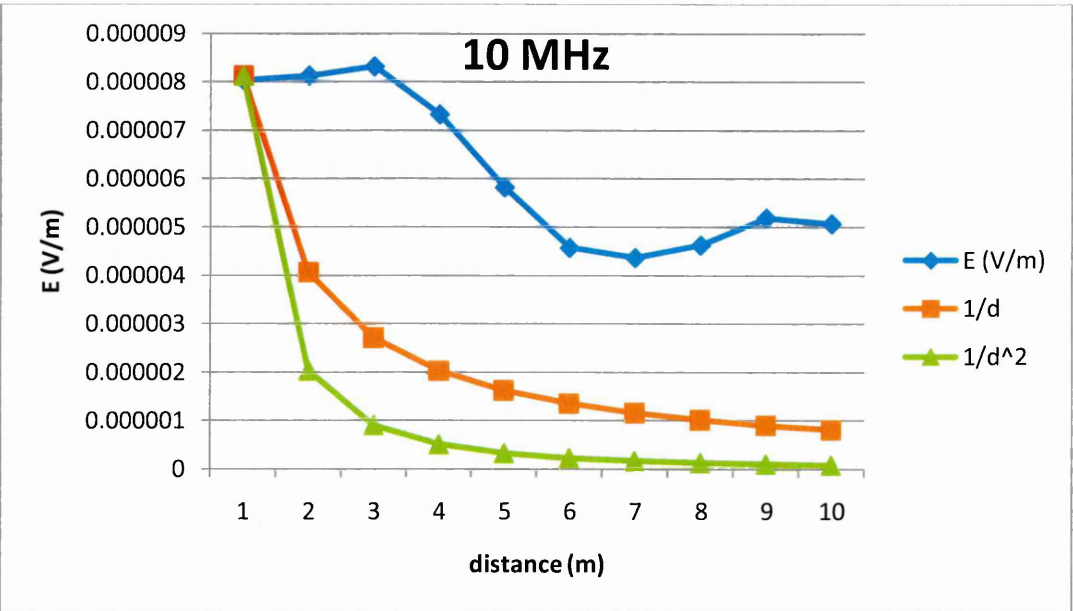
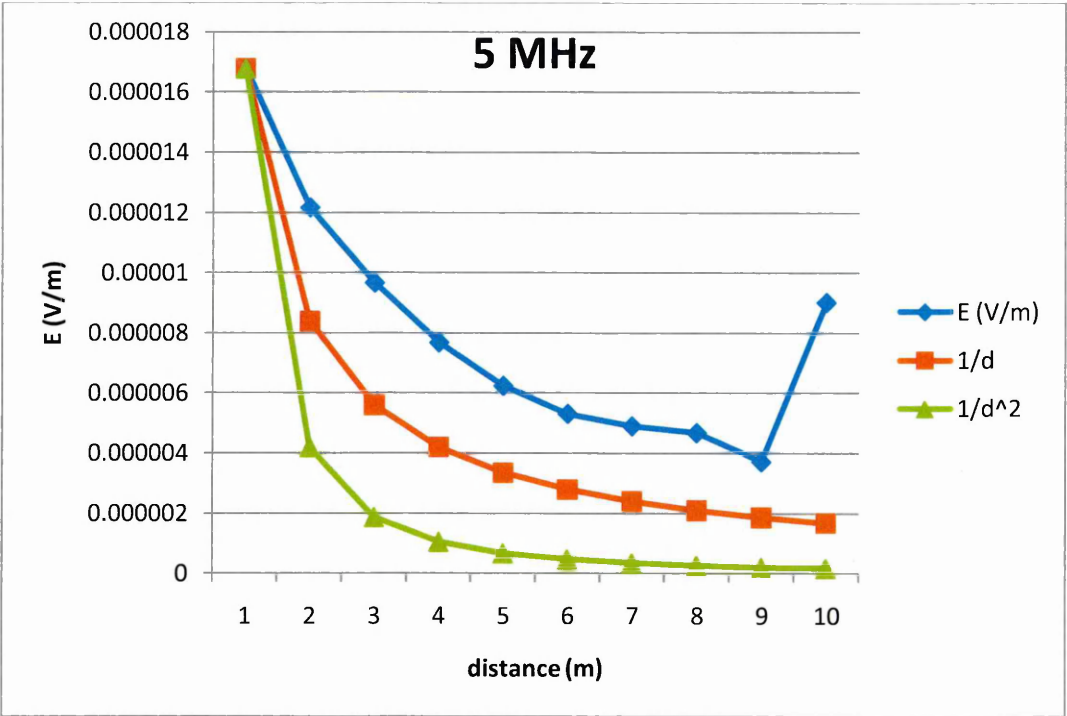
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	20	26	1.99526E-05
2	20	25.1	1.79887E-05
3	20	24.1	1.60325E-05
4	20	23.6	1.51356E-05
5	20	22.3	1.30317E-05
6	20	21	1.12202E-05
7	20	20.2	1.02329E-05
8	20	19.7	9.66051E-06
9	20	18.4	8.31764E-06
10	20	18.2	8.12831E-06

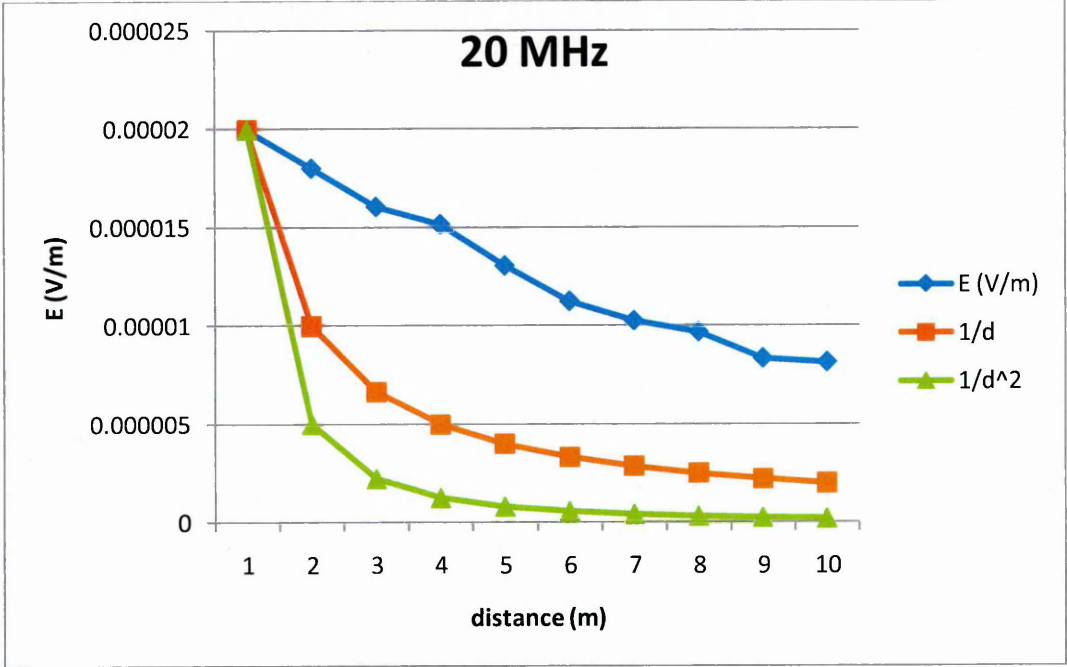
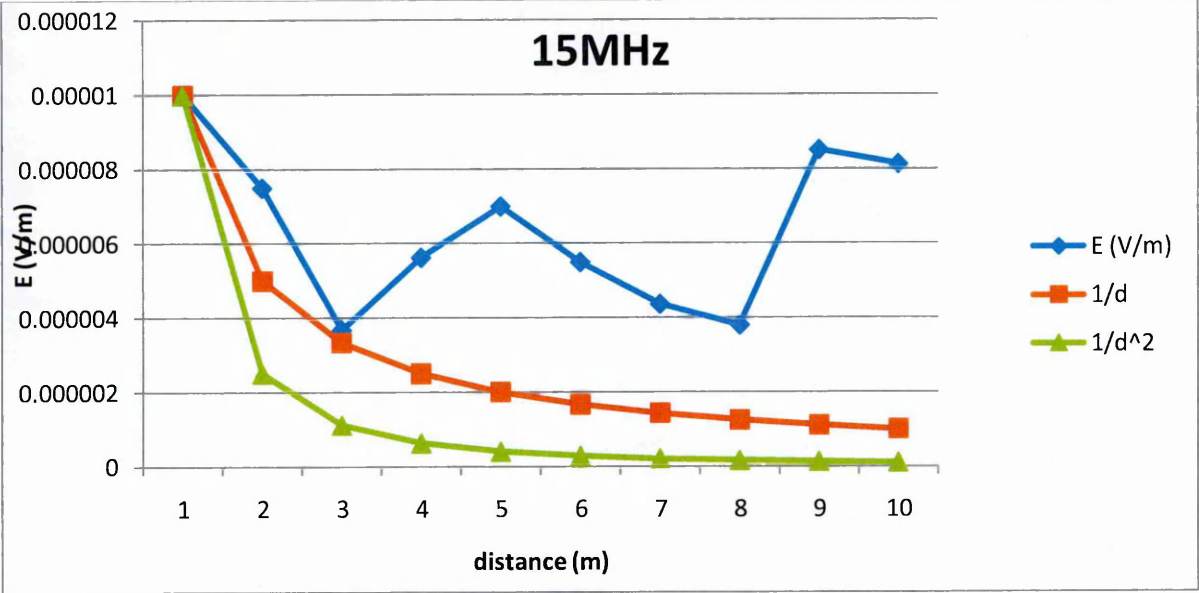
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	25	31.8	3.89045E-05
2	25	30.9	3.50752E-05
3	25	28.9	2.78612E-05
4	25	28.8	2.75423E-05
5	25	29.1	2.85102E-05
6	25	27.2	2.29087E-05
7	25	27	2.23872E-05
8	25	26.7	2.16272E-05
9	25	23.6	1.51356E-05
10	25	21.4	1.1749E-05

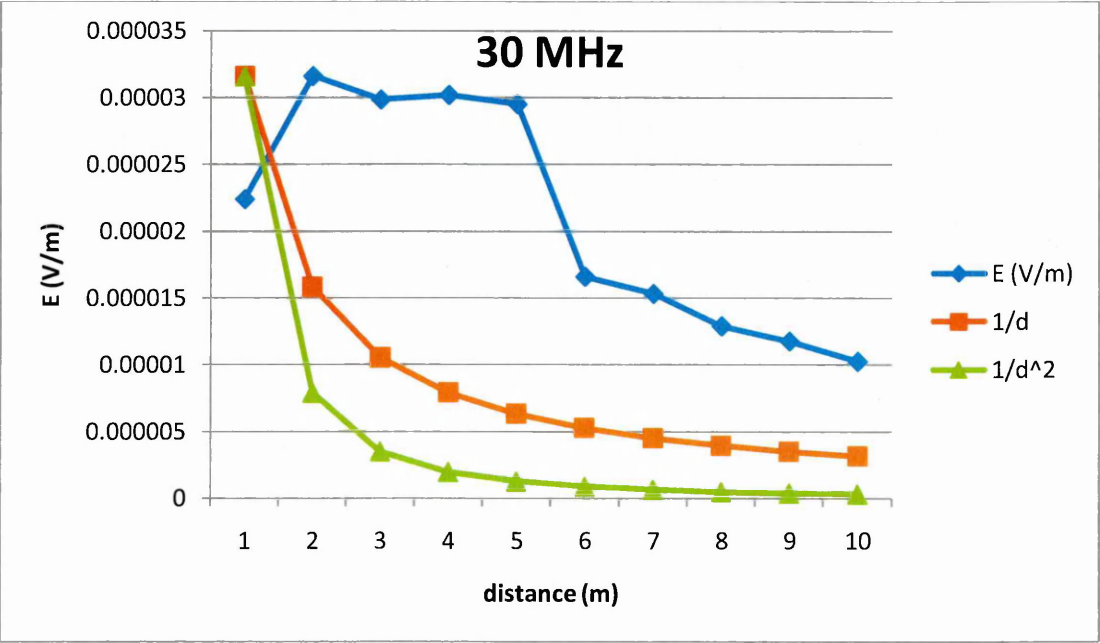
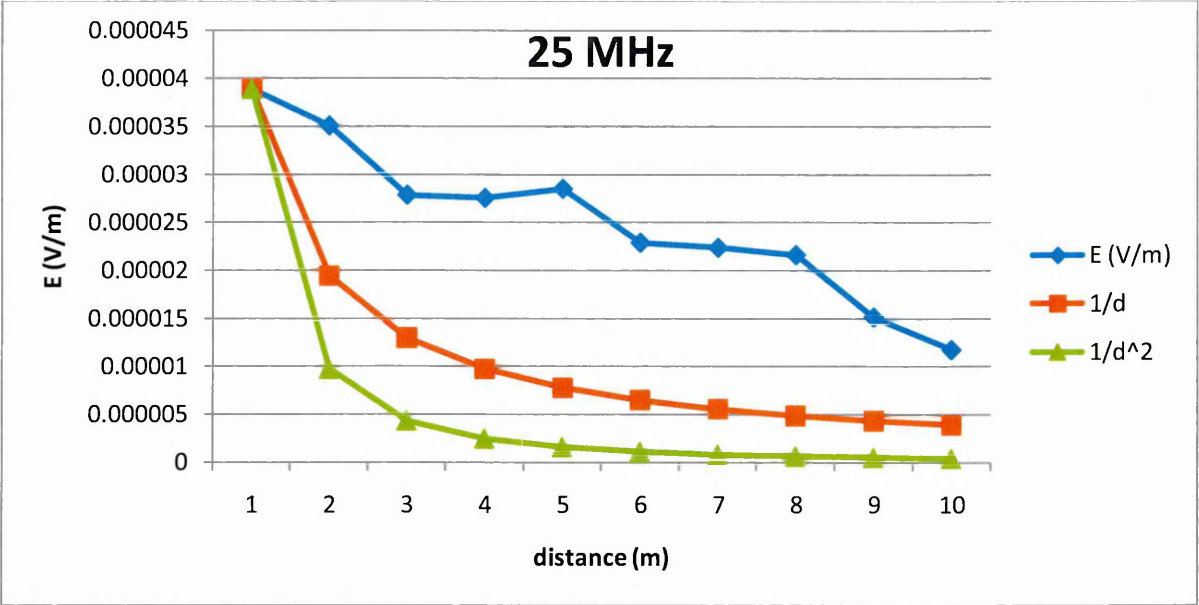
Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	30	27	2.23872E-05
2	30	30	3.16228E-05
3	30	29.5	2.98538E-05
4	30	29.6	3.01995E-05
5	30	29.4	2.95121E-05
6	30	24.4	1.65959E-05
7	30	23.7	1.53109E-05
8	30	22.2	1.28825E-05
9	30	21.4	1.1749E-05
10	30	20.2	1.02329E-05

The following graphs are those that have been plotted from each table above with the ambient noise subtracted.









**APPENDIX D: RADIATED EMISSIONS, BRADLEY STOKE, WHIP ANTENNA,
AMBIENT SUBTRACTED, 20V INJECTED**

The following measurements were taken on the 6th – 21st of January 2005 in

Bradley Stoke, Bristol for a 20V injected signal. The whip antenna was positioned at various distances from the front of the premises.

Frequency (MHz)	Monopole (dBµV/m)
1.6	32
5	36
10	23
15	27
20	27
25	25
30	23

Ambient radiated emission

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	1.6	56	0.000630957
2	1.6	49	0.000281838
3	1.6	43	0.000141254
4	1.6	40	0.0001
5	1.6	36	6.30957E-05
6	1.6	36	6.30957E-05
7	1.6	22	1.25893E-05
8	1.6	14	5.01187E-06
9	1.6	8	2.51189E-06
10	1.6	39	8.91251E-05

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	5	53	0.000446684
2	5	47	0.000223872
3	5	43	0.000141254
4	5	41	0.000112202
5	5	36	6.30957E-05
6	5	37	7.07946E-05
7	5	35	5.62341E-05
8	5	37	7.07946E-05
9	5	37	7.07946E-05
10	5	35	5.62341E-05

Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	10	43	0.000141254
2	10	38	7.94328E-05
3	10	37	7.07946E-05
4	10	37	7.07946E-05
5	10	36	6.30957E-05
6	10	38	7.94328E-05
7	10	38	7.94328E-05
8	10	37	7.07946E-05
9	10	37	7.07946E-05
10	10	31	3.54813E-05

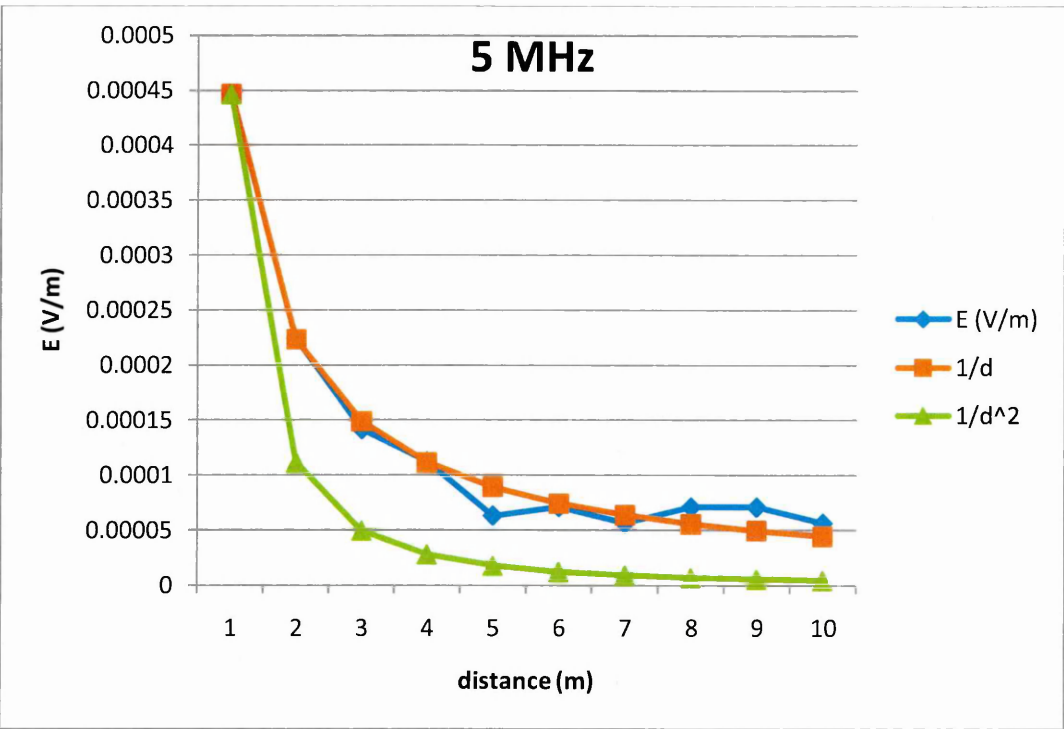
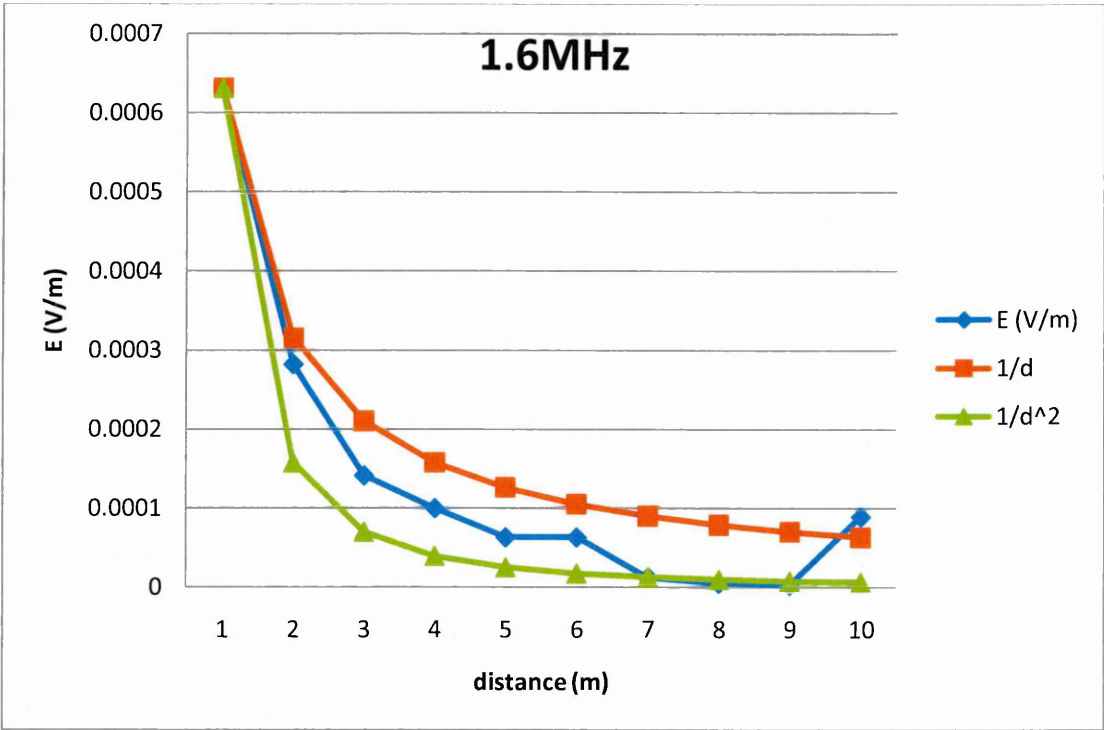
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	15	66	0.001995262
2	15	63	0.001412538
3	15	62	0.001258925
4	15	61	0.001122018
5	15	60	0.001
6	15	59	0.000891251
7	15	58	0.000794328
8	15	58	0.000794328
9	15	57	0.000707946
10	15	59	0.000891251

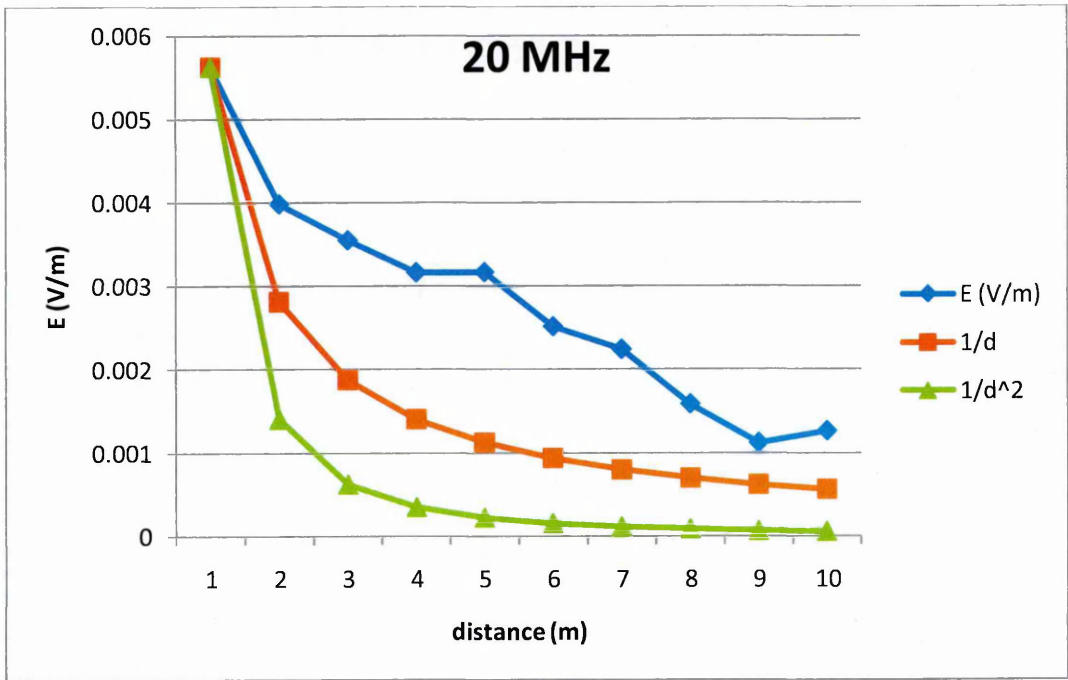
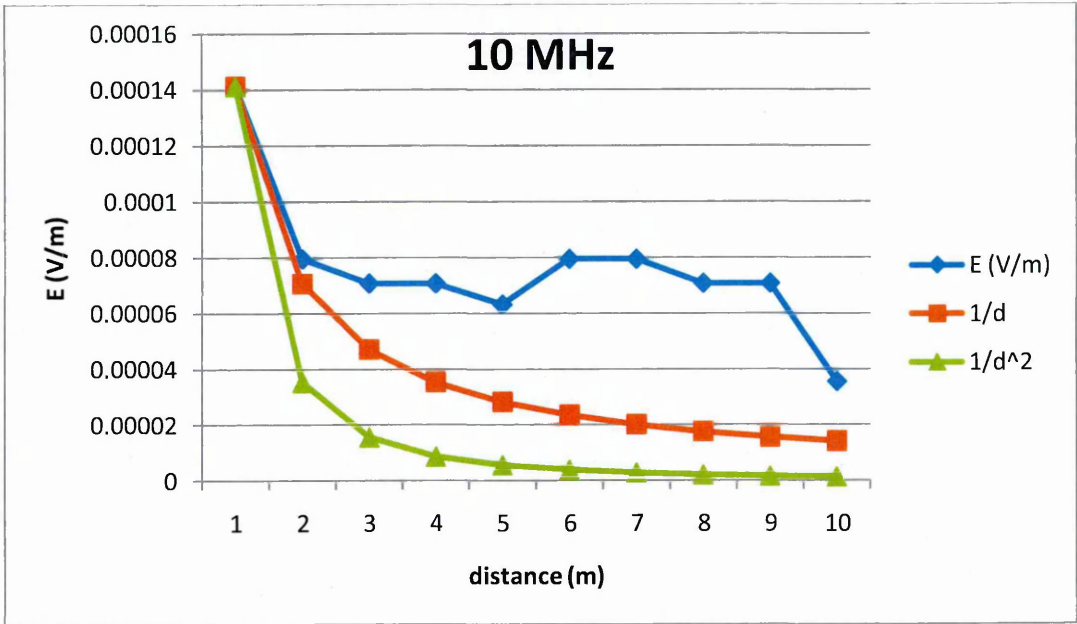
Distance (m)	Frequency (MHz)	E (dBµV/m)	E (V/m)
1	20	75	0.005623413
2	20	72	0.003981072
3	20	71	0.003548134
4	20	70	0.003162278
5	20	70	0.003162278
6	20	68	0.002511886
7	20	67	0.002238721
8	20	64	0.001584893
9	20	61	0.001122018
10	20	62	0.001258925

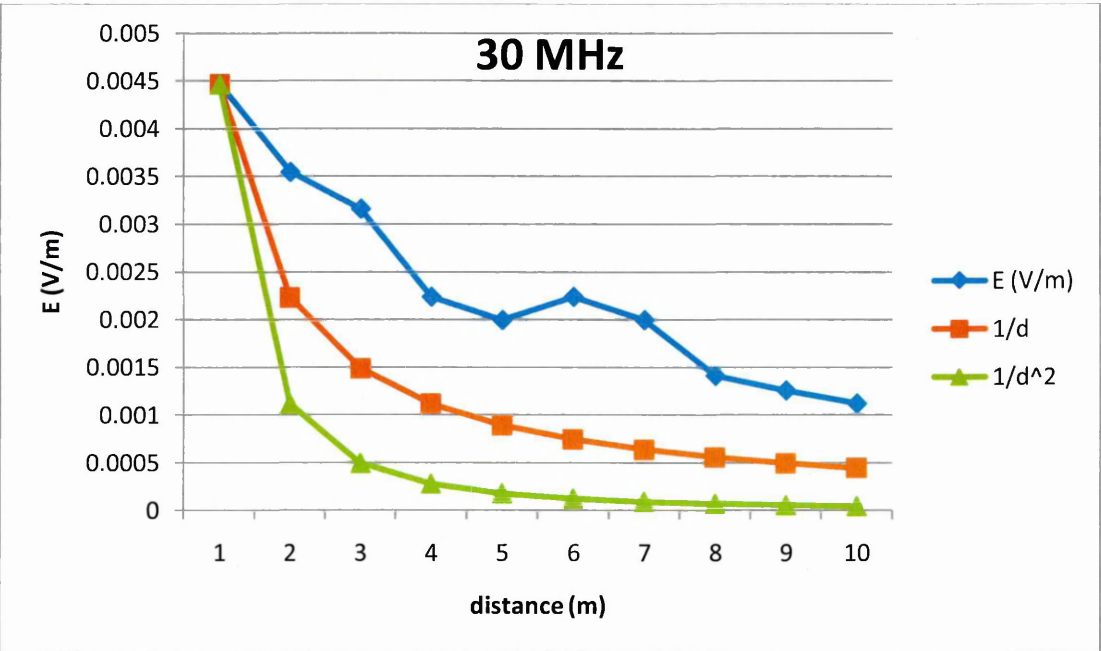
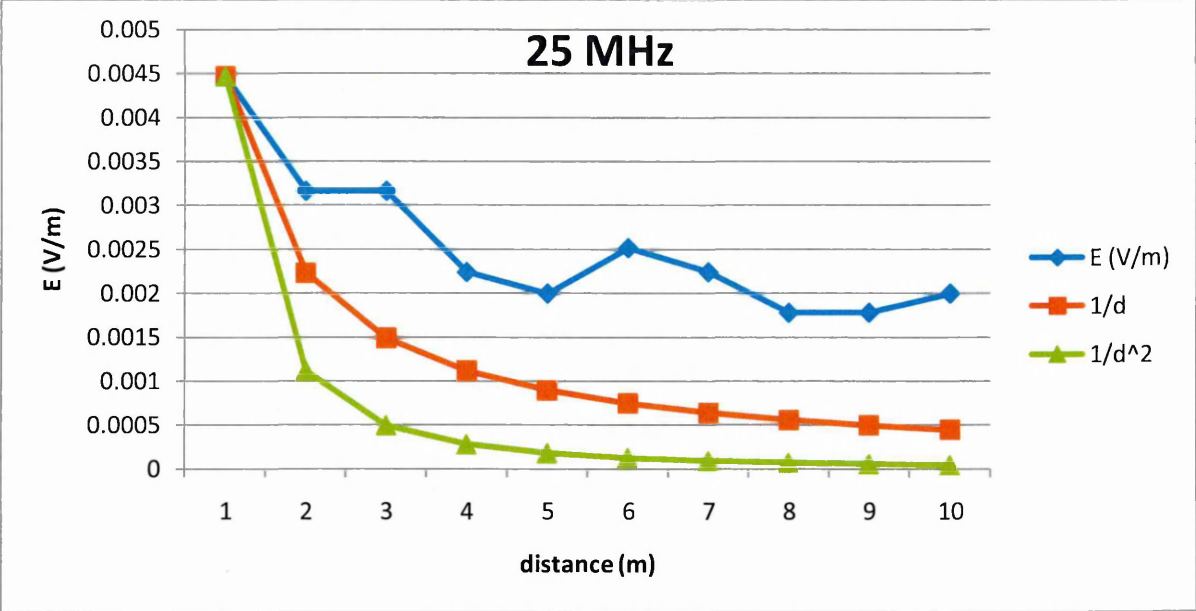
Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	25	73	0.004466836
2	25	70	0.003162278
3	25	70	0.003162278
4	25	67	0.002238721
5	25	66	0.001995262
6	25	68	0.002511886
7	25	67	0.002238721
8	25	65	0.001778279
9	25	65	0.001778279
10	25	66	0.001995262

Distance (m)	Frequency (MHz)	E (dBμV/m)	E (V/m)
1	30	73	0.004466836
2	30	71	0.003548134
3	30	70	0.003162278
4	30	67	0.002238721
5	30	66	0.001995262
6	30	67	0.002238721
7	30	66	0.001995262
8	30	63	0.001412538
9	30	62	0.001258925
10	30	61	0.001122018

The following graphs are those that have been plotted from each table above with the ambient noise subtracted.







APPENDIX E: CONTROL SOFTWARE DEVELOPED TO PROGRAMME THE ANRITSU

420B NETWORK ANALYSER

```
unit UnitFinal;
(* Delphi program to automate the OU ANRITSU Network analyser *)
(* With the wellbrook loop. Not antenna factor is added in spreadsheet *)
(* ===== *)
* This program reads 250 measurements from the ANRITSU between 1.6 and 30MHz*
* The status variables IBSTA (Interface Bus Status), IBERR (Interface Bus Error), and
IBCNTL (Interface Bus Control) are defined in the VAR section below. Each bit of IBSTA
and each value of IBERR are defined in the CONST section below as a mnemonic constant
for easy recognition. In this example, these mnemonic definitions are logically ANDed with
the variable IBSTA to determine if a particular bit has been set. The mnemonic definitions
are equated with the variable IBERR to determine the error code. The procedure GPIBERR
is called when a NI-488 function fails. The error message is printed along with the status
variables IBSTA, IBERR, and IBCNTL in message pop up dialog boxes. The procedure
AnritsuERR is called when the serial poll response byte indicates the Anritsu does not have
valid data to send. The error message and the serial poll response byte are printed in a
message pop up dialog box. The NI-488 function ibonl (Interface Bus Online) is called from
the TForm1.Button1Click procedure and from the two procedures, GPIBERR and
AnritsuERR. When the second parameter of the function ibonl is zero, the software and the
hardware are disabled. Execution of this program is terminated after the call to the function
ibonl to disable the software and hardware. The function HALT is used to terminate this
program within the procedures GPIBERR and AnritsuERR.
* ===== *)
interface
uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls;
type
  TForm1 = class(TForm)
    Button1: TButton;
    Button2: TButton;
    Memo1: TMemo;
    ComboBox1: TComboBox;
    procedure Button2Click(Sender: TObject); (* Procedure to Exit. *)
    procedure Button1Click(Sender: TObject); (* Procedure to run test. *)
    procedure FormCreate(Sender: TObject); (* Procedure to create an empty file *)
  private
    { Private declarations }
  public
    { Public declarations }
  end;
const
  (* GPIB status bit definitions. *)
  ERR = $8000; (* Error detected *)
  TIMO = $4000; (* Timeout *)
  ENDgpib = $2000; (* EOI or EOS detected *)
  SRQI = $1000; (* SRQ detected by CIC *)
  RQS = $800; (* Device needs service *)
  SPOLL = $400; (* Board has been serially polled *)
  EVENT = $200; (* An event has occurred *)
```

```

CMPL = $100;    (* I/O completed *)
LOK = $80;      (* Local lockout state *)
REM = $40;      (* Remote state *)
CIC = $20;      (* Controller-in-charge *)
ATN = $10;      (* Attention asserted *)
TACS = $8;      (* Talker active *)
LACS = $4;      (* Listener active *)
DTAS = $2;      (* Device trigger state *)
DCAS = $1;      (* Device clear state *)

```

(* Error messages returned in global variable IBERR: *)

```

EDVR = 0;      (* System error *)
ECIC = 1;      (* Function requires GPIB board to be CIC *)
ENOL = 2;      (* Write function detected no Listeners *)
EADR = 3;      (* Interface board not addressed correctly *)
EARG = 4;      (* Invalid argument to function call *)
ESAC = 5;      (* Function requires GPIB board to be SAC *)
EABO = 6;      (* I/O operation aborted *)
ENEB = 7;      (* Non-existent interface board *)
EDMA = 8;      (* Error performing DMA *)
EOIP = 10;     (* I/O operation started before previous *)
               (* operation completed *)
ECAP = 11;     (* No capability for intended operation *)
EFSO = 12;     (* File system operation error *)
EBUS = 14;     (* Command error during device call *)
ESTB = 15;     (* Serial poll status byte lost *)
ESRQ = 16;     (* SRQ remains asserted *)
ETAB = 20;     (* The return buffer is full *)

```

(* Timeout values and meanings: *)

```

TNONE = 0;     (* Infinite timeout (disabled) *)
T10us = 1;     (* Timeout of 10 microseconds (ideal) *)
T30us = 2;     (* Timeout of 30 microseconds (ideal) *)
T100us = 3;    (* Timeout of 100 microseconds (ideal) *)
T300us = 4;    (* Timeout of 300 microseconds (ideal) *)
T1ms = 5;      (* Timeout of 1 milliseconds (ideal) *)
T3ms = 6;      (* Timeout of 3 milliseconds (ideal) *)
T10ms = 7;     (* Timeout of 10 milliseconds (ideal) *)
T30ms = 8;     (* Timeout of 30 milliseconds (ideal) *)
T100ms = 9;    (* Timeout of 100 milliseconds (ideal) *)
T300ms = 10;   (* Timeout of 300 milliseconds (ideal) *)
T1s = 11;      (* Timeout of 1 second (ideal) *)
T3s = 12;      (* Timeout of 3 seconds (ideal) *)
T10s = 13;     (* Timeout of 10 seconds (ideal) *)
T30s = 14;     (* Timeout of 30 seconds (ideal) *)
T100s = 15;    (* Timeout of 100 seconds (ideal) *)
T300s = 16;    (* Timeout of 300 seconds (ideal) *)
T1000s = 17;   (* Timeout of 1000 seconds (ideal) *)

```

```

CR = Chr(10);
LF = Chr(13);
AnritsuAddress = 7;
NumberOfReadings = 250;

```

type

```

(* Type declarations for exported NI-488.2 Global Variables.      *)
Tibsta = function : integer; stdcall;
Tiberr = function : integer; stdcall;
Tibcntl = function : Longint; stdcall;

(* Type declarations for exported NI-488 functions.              *)
Tibclr = function (ud : integer) : integer; stdcall;

Tibdev = function(ud: integer;
                  pad: integer;
                  sad: integer;
                  tmo: integer;
                  eot: integer;
                  eos: integer) : integer; stdcall;

Tibonl = function(ud: integer;
                  v: integer) : integer; stdcall;

Tibrd = function (ud: integer;
                  var rdBuf;
                  cnt: Longint) : integer; stdcall;

Tibrsp = function (ud: integer;
                  var spr: byte) : integer; stdcall;

Tibtrg = function (ud : integer) : integer; stdcall;

Tibwait = function (ud: integer;
                   mask: integer) : integer; stdcall;

Tibwrt = function (ud: integer;
                   var wrtbuf;
                   cnt: longint) : integer; stdcall;
Tibtmo = function (ud: integer; v: integer) : integer; stdcall;

var
Form1: TForm1;
(* Addresses for NI-488.2 GPIB global status variables          *)
AddrIbsta : Tibsta;
AddrIberr : Tiberr;
AddrIbcntl : Tibcntl;

(* Pointers to the NI-488.2 GPIB global status variables        *)
Pibsta : ^integer;
Piberr : ^integer;
Pibcntl : ^Longint;

(* Declaration for the Handle for the GPIB library              *)
Gpib32Lib: THandle;

(* Declarations for the NI-488 GPIB calls                        *)
ibclr : Tibclr;
ibdev : Tibdev;
ibonl : Tibonl;
ibrd : Tibrd;

```



```

ibrsp : Tibrsp;
ibtrg : Tibtrg;
ibwait : Tibwait;
ibwrt : Tibwrt;
ibtmo : Tibtmo;

```

```

Anritsu : integer;      (* Device number *)
MyFile : TextFile;
activeFileName:String;  {the file that all data will be saved to}

```

```

data : array[0..NumberOfReadings] of string;
distance : array[0..NumberOfReadings] of string;
frequency : array[0..NumberOfReadings] of string;

```

implementation

```
{$R *.DFM}
```

```
(*
```

```
=====
*          Procedure loadDLL
```

```

* This procedure loads the GPIB-32.DLL library. If the LoadLibrary
* call is successful, the next step is to get the addresses of the
* global status variables and functions using GetProcAddress. If the
* GetProcAddress calls were successful, the procedure returns to the
* main routine. Otherwise, it will free the library and HALT.

```

```

* The HALT function will terminate this program.
*
=====

```

```
*)
```

```
procedure loadDLL;
```

```
var
```

```
  str : string;
```

```
begin
```

```
  (* Load the GPIB-32.DLL library using the LoadLibrary function. *)
```

```
  Gpib32Lib := LoadLibrary('GPIB-32.DLL');
```

```
  (* Check to see if library loaded successfully. If the library could *)
```

```
  (* not be loaded, display an error message and then HALT the program. *)
```

```
  If Gpib32Lib = 0 Then
```

```
    Begin
```

```
      str := 'LoadLibrary FAILED!';
```

```
      MessageDlg(str, mtError, [mbOK], 0);
```

```
      halt;
```

```
    End;
```

```
  (* Get the addresses of the GPIB Global Variables. *)
```

```
  @AddrIbsta := GetProcAddress(Gpib32Lib, 'user_ibsta');
```

```
  @AddrIberr := GetProcAddress(Gpib32Lib, 'user_iberr');
```

```
  @AddrIbcntl := GetProcAddress(Gpib32Lib, 'user_ibcntl');
```

```
  (* Get the addresses of the functions needed for this application. *)
```

```
  @ibclr := GetProcAddress(Gpib32Lib, 'ibclr');
```

```
  @ibdev := GetProcAddress(Gpib32Lib, 'ibdev');
```

```

@ibonl := GetProcAddress(Gpib32Lib, 'ibonl');
@ibrd  := GetProcAddress(Gpib32Lib, 'ibrd');
@ibrsp := GetProcAddress(Gpib32Lib, 'ibrsp');
@ibtrg := GetProcAddress(Gpib32Lib, 'ibtrg');
@ibwait := GetProcAddress(Gpib32Lib, 'ibwait');
@ibwrt  := GetProcAddress(Gpib32Lib, 'ibwrt');
@ibtmo  := GetProcAddress(Gpib32Lib, 'ibtmo');

(* Verify that addresses were obtained. If unable to get any one of *)
(* the addresses, then free the library, display an error message and *)
(* HALT the program. *)
if (@Addrlbsta = NIL) Or
   (@Addrlberr = NIL) Or
   (@Addrlbcntl = NIL) Or
   (@ibclr    = NIL) Or
   (@ibdev    = NIL) Or
   (@ibonl    = NIL) Or
   (@ibrd     = NIL) Or
   (@ibrsp    = NIL) Or
   (@ibtrg    = NIL) Or
   (@ibwait   = NIL) Or
   (@ibwrt    = NIL) Or
   (@ibtmo    = NIL) Then
Begin
  str := 'GetProcAddress FAILED!';
  MessageDlg(str, mtError, [mbOK], 0);
  (* Free the GPIB library. *)
  FreeLibrary(Gpib32Lib);
  halt;
End;

(* Initialize GPIB global pointers to point to address location *)
Pibsta := @Addrlbsta;
Piberr := @Addrlberr;
Pibcntl := @Addrlbcntl;
end;

(*
=====
*           Procedure AnritsuERR
* This procedure will notify you that the Anritsu returned an invalid
* serial poll response byte. The error message will be printed along
* with the serial poll response byte in a pop up message box.
*
* The NI-488 function ibonl is called to disable the hardware and
* software.
*
* The HALT function will terminate this program.
*
=====
*)
procedure Anritsuerr(msg: string; spr: byte);
var
  str : string;  (* String used for displaying messages. *)

```

```

tempStr : string;    (* String used for conversions.    *)

begin
  tempStr := IntToHex(spr, 2);
  str := msg + ' Status Byte = $' + tempStr;
  MessageDlg(str, mtError, [mbOK], 0);

  (* Call the ibonl function to disable the hardware and software.    *)
  ibonl(Anritsu, 0);
  (* Free the GPIB library.    *)
  FreeLibrary(Gpib32Lib);

  halt;
end;

(*
=====
*           Procedure GPIBERR
* This procedure will notify you that a NI-488 function failed by
* printing an error message. The status variable IBSTA will be printed
* in hexadecimal along with the mnemonic meaning of the bit position. The
* status variable IBERR will be printed in decimal along with the
* mnemonic meaning. The status variable IBCNTL will be printed in decimal.
*
* The NI-488 function ibonl is called to disable the hardware and
* software.
*
* The HALT command stops execution of this program.
*
=====
*)
procedure gpiberr(msg: string);
var
  str      : string;    (* String used for displaying messages.    *)
  ibstaStr : string;    (* String for converting IBSTA.    *)
  iberrStr : string;    (* String for converting IBERR.    *)
  ibcntlStr : string;   (* String for converting IBCNTL.    *)

begin
  ibstaStr := IntToHex(Pibsta^, 4);
  iberrStr := IntToStr(Piberr^);
  str := msg + ' ibsta = $' + ibstaStr + ' iberr = ' + iberrStr;
  MessageDlg(str, mtError, [mbOK], 0);

  str := 'ibsta ==> ';
  if (Pibsta^ and ERR) <> 0 Then
    str := Concat(str, ' ERR');
  if (Pibsta^ and TIMO) <> 0 Then
    str := Concat(str, ' TMO');
  if (Pibsta^ and ENDgpib) <> 0 Then
    str := Concat(str, ' END');
  if (Pibsta^ and SRQI) <> 0 Then
    str := Concat(str, ' SRQI');
  if (Pibsta^ and RQS) <> 0 Then

```

```

str := Concat(str, ' RQS');
if (Pibsta^ and SPOLL) <> 0 Then
str := Concat(str, ' SPOLL');
if (Pibsta^ and EVENT) <> 0 Then
str := Concat(str, ' EVENT');
if (Pibsta^ and CMPL) <> 0 Then
str := Concat(str, ' CMPL');
if (Pibsta^ and LOK) <> 0 Then
str := Concat(str, ' LOK');
if (Pibsta^ and REM) <> 0 Then
str := Concat(str, ' REM');
if (Pibsta^ and CIC) <> 0 Then
str := Concat(str, ' CIC');
if (Pibsta^ and ATN) <> 0 Then
str := Concat(str, ' ATN');
if (Pibsta^ and TACS) <> 0 Then
str := Concat(str, ' TACS');
if (Pibsta^ and LACS) <> 0 Then
str := Concat(str, ' LACS');
if (Pibsta^ and DTAS) <> 0 Then
str := Concat(str, ' DTAS');
if (Pibsta^ and DCAS) <> 0 Then
str := Concat(str, ' DCAS');

```

```

MessageDlg(str, mtError, [mbOK], 0);

```

```

str := 'liberr ===> ';
if Piberr^ = EDVR Then
str := Concat(str, ' EDVR');
if Piberr^ = ECIC Then
str := Concat(str, ' ECIC');
if Piberr^ = ENOL Then
str := Concat(str, ' ENOL');
if Piberr^ = EADR Then
str := Concat(str, ' EADR');
if Piberr^ = EARG Then
str := Concat(str, ' EARG');
if Piberr^ = ESAC Then
str := Concat(str, ' ESAC');
if Piberr^ = EABO Then
str := Concat(str, ' EABO');
if Piberr^ = ENEB Then
str := Concat(str, ' ENEB');
if Piberr^ = EDMA Then
str := Concat(str, ' EDMA');
if Piberr^ = EOIP Then
str := Concat(str, ' EOIP');
if Piberr^ = ECAP Then
str := Concat(str, ' ECAP');
if Piberr^ = EFSO Then
str := Concat(str, ' EFSO');
if Piberr^ = EBUS Then
str := Concat(str, ' EBUS');
if Piberr^ = ESTB Then
str := Concat(str, ' ESTB');

```

```

if Piberr^ = ESRQ Then
  str := Concat(str, ' ESRQ');
if Piberr^ = ETAB Then
  str := Concat(str, ' ETAB');

MessageDlg(str, mtError, [mbOK], 0);

ibcntlStr := IntToStr(Pibcntl^);
str := 'ibcntl = ' + ibcntlStr;
MessageDlg(str, mtError, [mbOK], 0);

(* Call the ibonl function to disable the hardware and software. *)
ibonl(Anritsu, 0);
(* Free the GPIB library. *)
FreeLibrary(Gpib32Lib);

halt;
end;

(*
=====
* Procedure TForm1.Button2Click
* This procedure is activated when the QUIT button is clicked. This
* procedure terminates the program.
*
=====
*)
procedure TForm1.Button2Click(Sender: TObject);
begin

(* If GPIB library is loaded, then free it before exiting the program. *)
if Gpib32Lib <> 0 then begin
  FreeLibrary(Gpib32Lib);
end;

Close;
end;

(*
=====
* Procedure TForm1.Button1Click
* This procedure is activated when the RUN button is clicked. This
* procedure reads 10 measurements from the Anritsu at the defined frequency and
bandwidth and calculates the average of the measurements.
*
=====
*)
procedure TForm1.Button1Click(Sender: TObject);
var
  msg : string; (* Display string. *)
  buf : packed array[0..100] of char; (* R/W buffer. *)
  data_buffer, freq_buf, frequency_buffer : string[10]; (* Assigned the value of RDBUF
which will *)
  i, j : integer; (* FOR loop index. *)
  DistanceCombo : string;

```

```

begin
(* Load the GPIB-32.DLL Library. *)
loadDLL;
(* Clear the List Box screen. *)
memo1.clear;
Anritsu := ibdev(0, AnritsuAddress, 0, 13, 1, 0); {Setup GPIB Board}
if (Anritsu < 0) THEN gpiberr('ibdev error');
buf := 'IN'+CR+LF; {Initialise Anritsu}
ibwrt(Anritsu, buf, 4);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'OP1'+CR+LF; {Set output to B}
ibwrt(Anritsu, buf, 5);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'IM0,0'+CR+LF; {Set Impedances to 75 ohm}
ibwrt(Anritsu, buf, 7);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'LLO'+CR+LF; {Set Output to 0dBm}
ibwrt(Anritsu, buf, 5);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'LW0'+CR+LF;
ibwrt(Anritsu, buf, 5); {Set Level Sweep Off}
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'CF0'+CR+LF; {Set Coupled to freq off}
ibwrt(Anritsu, buf, 5);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'TR0'+CR+LF; {Set trace to measure amplitudes (mag)}
ibwrt(Anritsu, buf, 5);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'FS1600000,30000000'+CR+LF; {Set sweep from 1.6MHz to 30MHz}
ibwrt(Anritsu, buf, 20);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
buf := 'BW8,9'+CR+LF; {Set bandwidth to 10kHz a Video BW to 30kHz}
ibwrt(Anritsu, buf, 7);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');

buf := 'ST60000'+CR+LF; {Set sweep time to 60 secs}
ibwrt(Anritsu, buf, 9);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
MessageDlg('Connect Output B directly to Input T to calibrate then press
OK',mtInformation,[mbOK],0);
buf := 'MS1'+CR+LF; {Set single weep mode and take reference sweep}
ibwrt(Anritsu, buf, 5);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
MessageDlg('Taking Reference Sweep - WAIT UNTIL SWEEP IS COMPLETE THEN
PRESS OK',mtInformation,[mbOK],0);
MessageDlg('Connect the PLT adaptor to OUTPUT B - the Antenna to INPUT T and
connect OUTPUT B directly to INPUT R using a 75 Ohm lead then press
OK',mtInformation,[mbOK],0);
buf := 'MS1'+CR+LF; {Single sweep with PLT adaptor and loop/whip attached}
ibwrt(Anritsu, buf, 5);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
MessageDlg('Taking Measurement - WAIT UNTIL SWEEP IS COMPLETE THEN PRESS
OK',mtInformation,[mbOK],0);
ibtmo(Anritsu,14);
buf := 'MMR1,250'+CR+LF; {measure using 250 data points}

```

```

ibwrt(Anritsu, buf, 10);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
{process data}
for i := 1 to 250 do    {read each point in turn back to PC}
begin
  ibrd(Anritsu,buf,9); {read 9 bytes of info from Anritsu}
  if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibrd Error');
  data_buffer := "";
  for j := 0 to Pibcntl^ do {go through each reading removing useless chars}
  begin
    {eg only 1 ..9, . , - are allowed}
    if (ord(buf[j]) >= 47) and (ord(buf[j]) <= 58) or (buf[j]='.') or (buf[j]='-') then
    begin
      data_buffer:= data_buffer+buf[j];
    end
  end;
end;

{fill data array}
data[i] := data_buffer;
{fill distance array}
DistanceCombo := ComboBox1.items[Combobox1.ItemIndex];
distance[i] := DistanceCombo;
end;
{process frequencies}
freq_buf := 'FQR1,250'+CR+LF; {measure using 250 data points}
ibwrt(Anritsu, freq_buf, 10);
if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibwrt Error');
for i := 1 to 250 do    {read each point in turn back to PC}
begin
  ibrd(Anritsu,freq_buf,13); {read 9 bytes of info from Anritsu}
  if (Pibsta^ AND ERR) <> 0 THEN gpiberr('ibrd Error');
  frequency_buffer := "";
  for j := 0 to Pibcntl^ do {go through each reading removing useless chars}
  begin
    {eg only 0 ..9, . , - are allowed}
    if (ord(freq_buf[j]) >= 47) and (ord(freq_buf[j]) <= 58) or (freq_buf[j]='.') then
    frequency_buffer:= frequency_buffer+freq_buf[j];
  end;
  frequency[i] := frequency_buffer;
end;
{output to screen}
for i := 1 to 250 do
begin
  msg := frequency[i] + ',' + data[i] + ',' + Distance[i];
  memo1.lines.add(msg); {output results}
end;
if (MessageDlg('Do you want to save
?',mtConfirmation,[mbYes,mbNo,mbCancel],0)=mrYes)
then
begin
  AssignFile(myFile,activeFileName);
  Append(myFile);
  for i := 0 to memo1.Lines.count do
    WriteLn(myFile, memo1.Lines[i]);
  CloseFile(myFile);
end;
{*****}

```

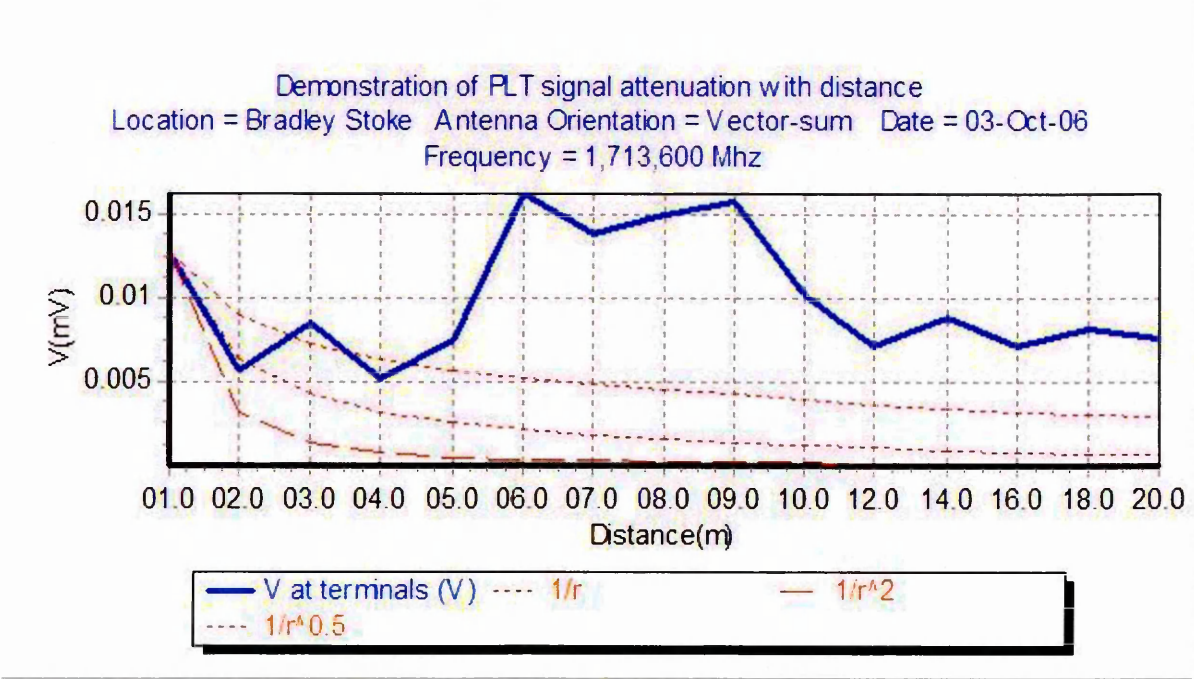
```

(* Call the ibonl function to disable the hardware and software. *)
  ibonl(Anritsu, 0);
end;
{*****}
procedure TForm1.FormCreate(Sender: TObject);
{this procedure prompts the user to nominate a file for all data.
Var saveDialog : TSaveDialog;
begin
  messageDlg('You will now be prompted to create a file to save
results',mtInformation,[mbOK],0);
  saveDialog := TSaveDialog.Create(self);
  saveDialog.InitialDir := GetCurrentDir;
  saveDialog.Filter := 'GPIB Data File *.csv';
  saveDialog.DefaultExt := 'csv';
  if saveDialog.Execute then
  begin
    AssignFile(myFile,saveDialog.FileName);
    ReWrite(myFile);
    WriteLn(myFile,'Frequency,Insertion Loss(dB),Distance (m)');
    CloseFile(myFile);
    activeFileName := saveDialog.FileName; {Save for use by append later}
  end;
  saveDialog.Free;
end;
end.

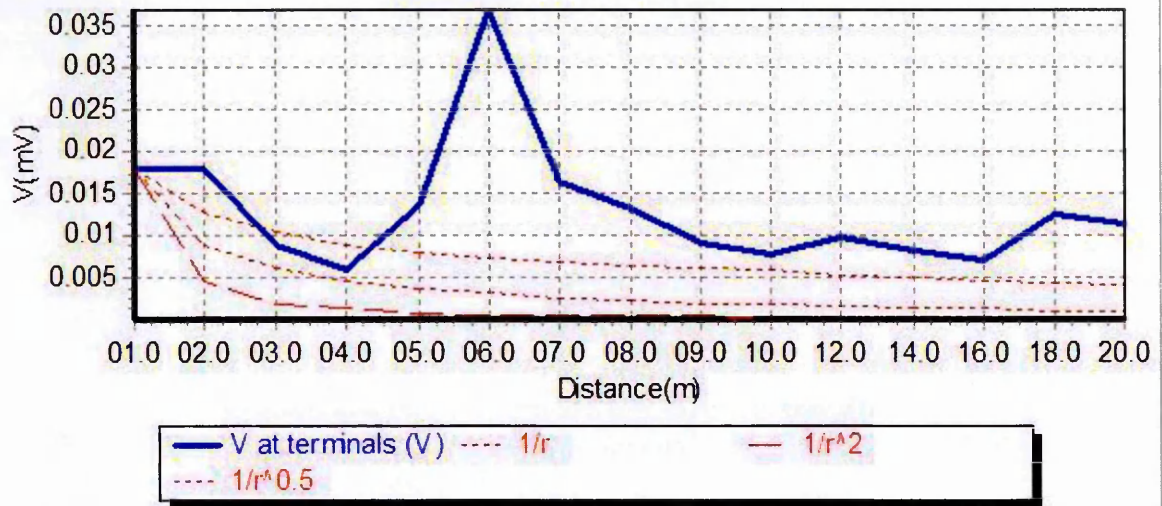
```


APPENDIX F: ATTENUATION WITH DISTANCE GRAPHS FOR BRADLEY STOKE
USING ANRITSU 420B

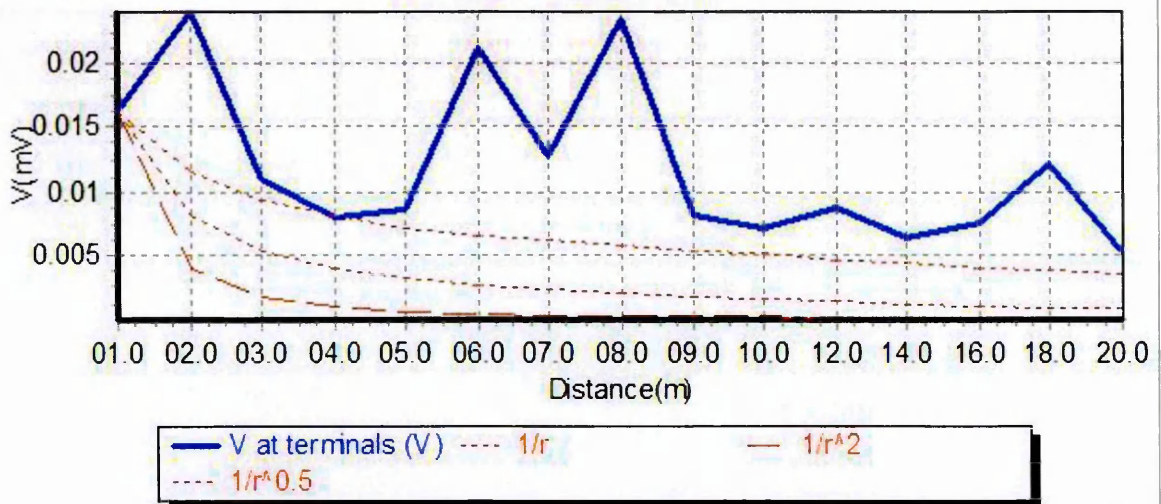
The following graphs were produced from data files produced by the Anritsu 420B network analyser during regressions measurements at Bradley Stoke, Bristol UK with a 0dBm injected signal. The Antenna was placed in both perpendicular and parallel orientations and the values vectorially summed. Software was written to extract 30 of the 250 frequencies and automatically populate the graphs.



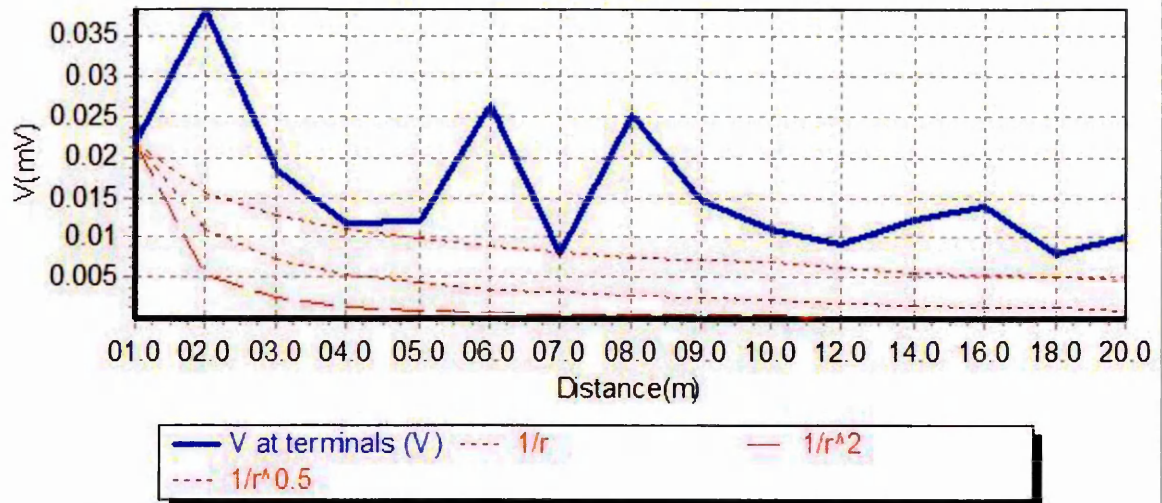
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 2,054,400 Mhz



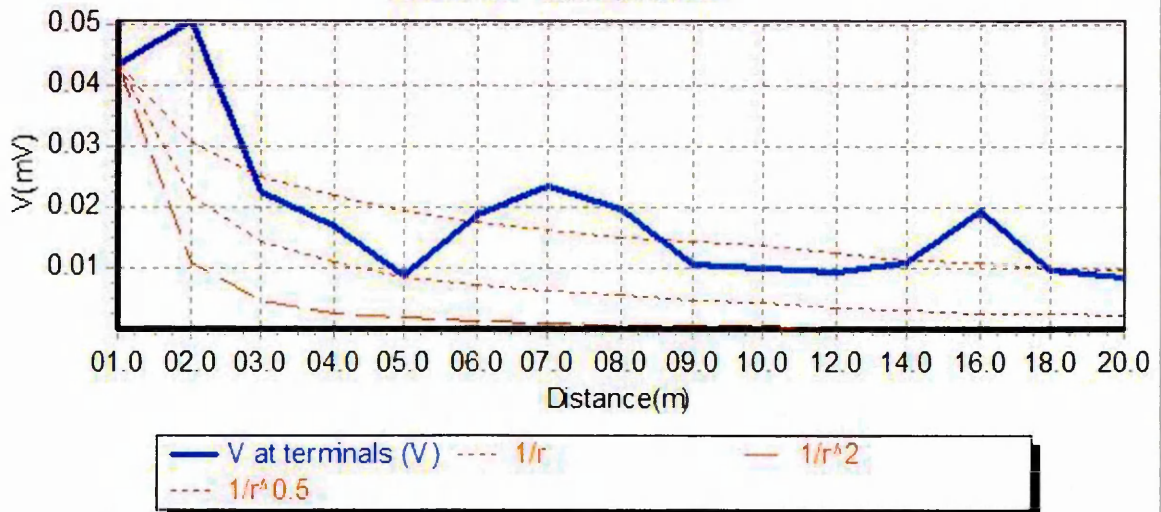
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 3,076,800 Mhz



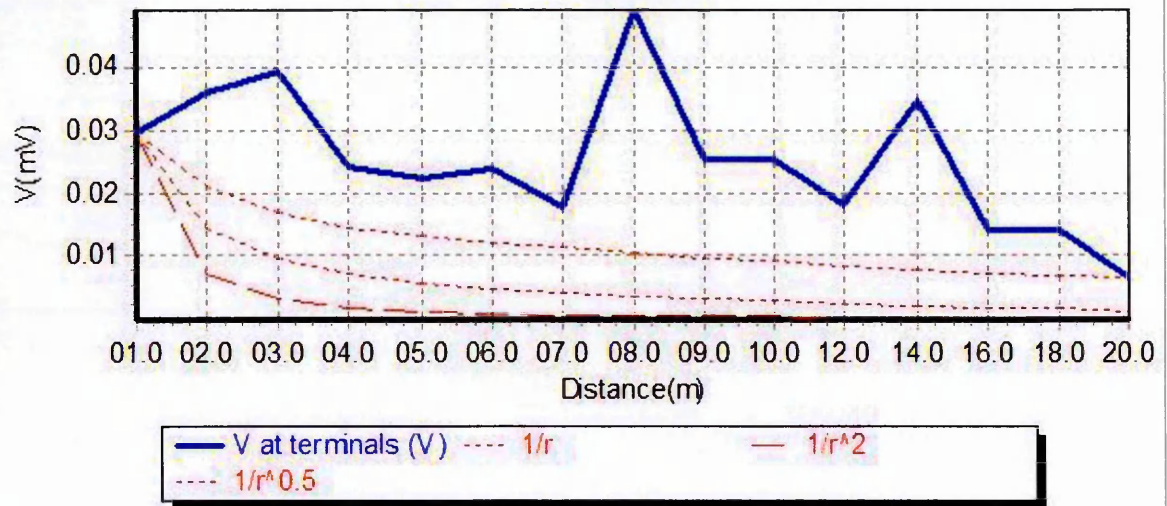
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 4,099,200 Mhz



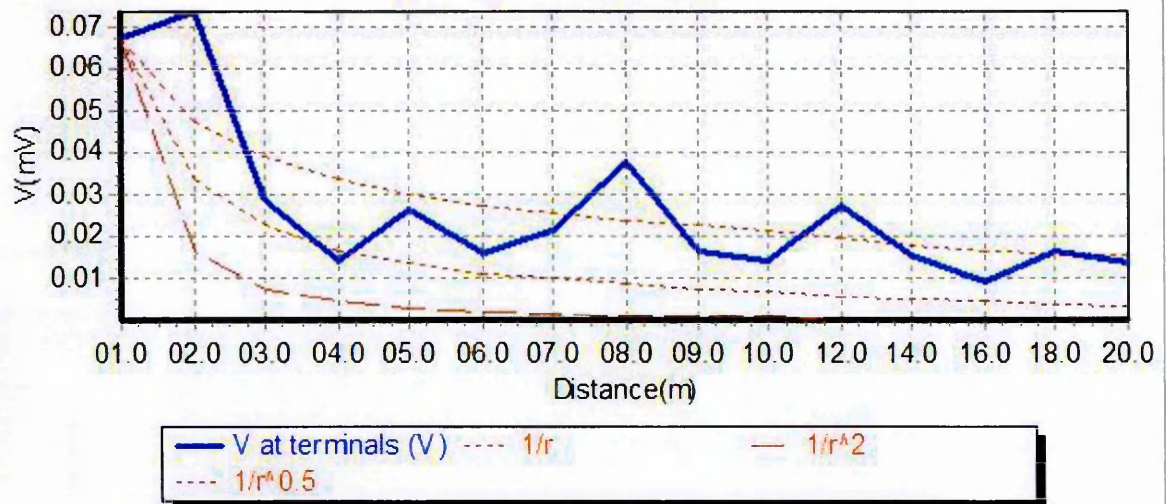
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 5,008,000 Mhz



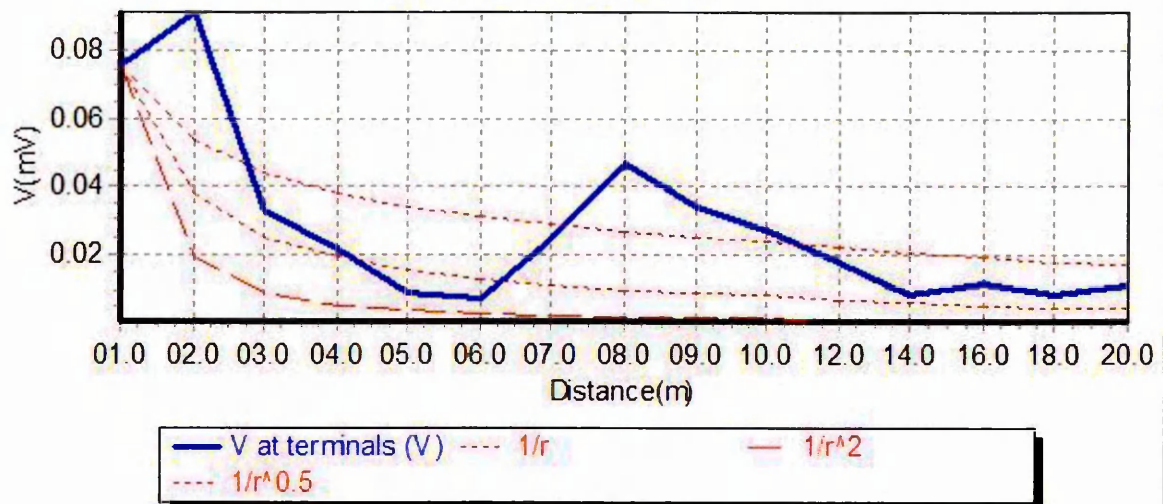
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 6,030,400 Mhz



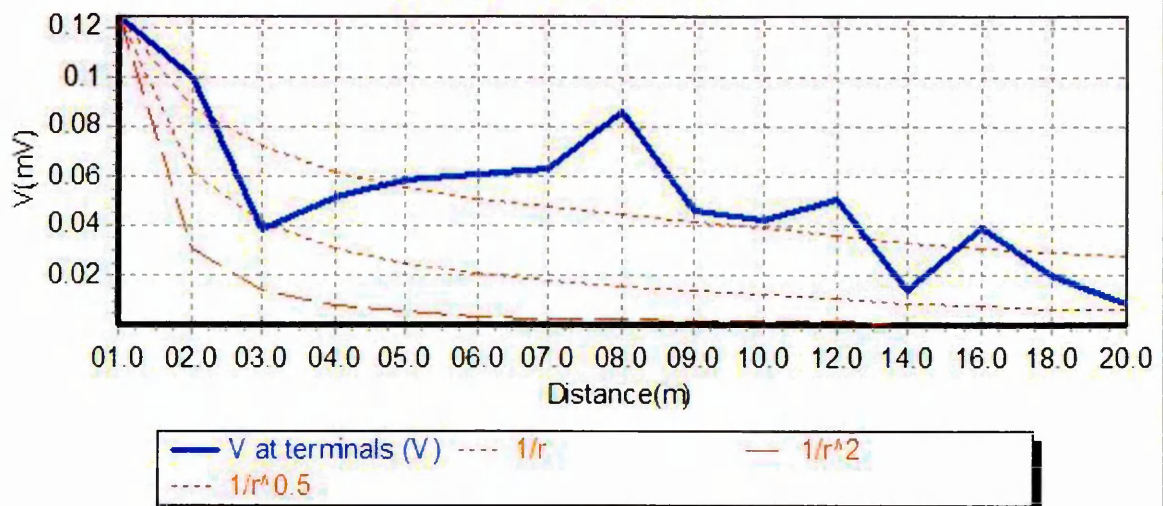
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 7,052,800 Mhz



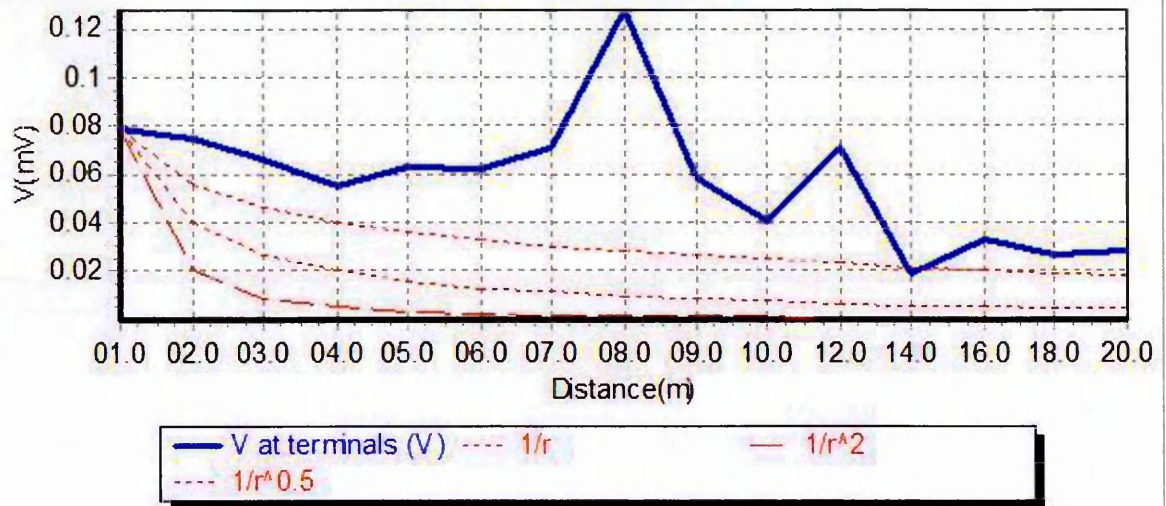
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 8,075,200 Mhz



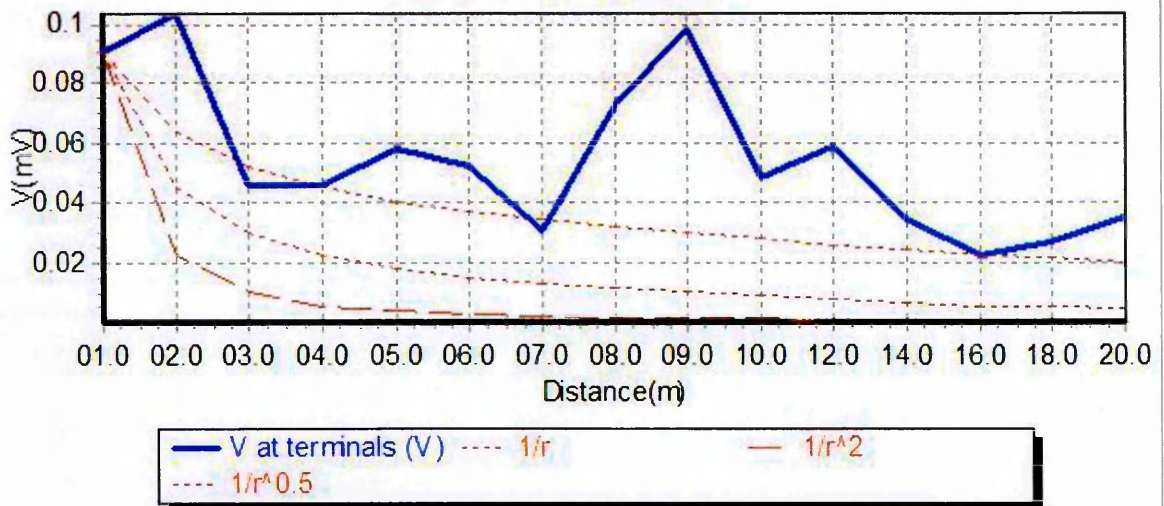
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 9,097,600 Mhz



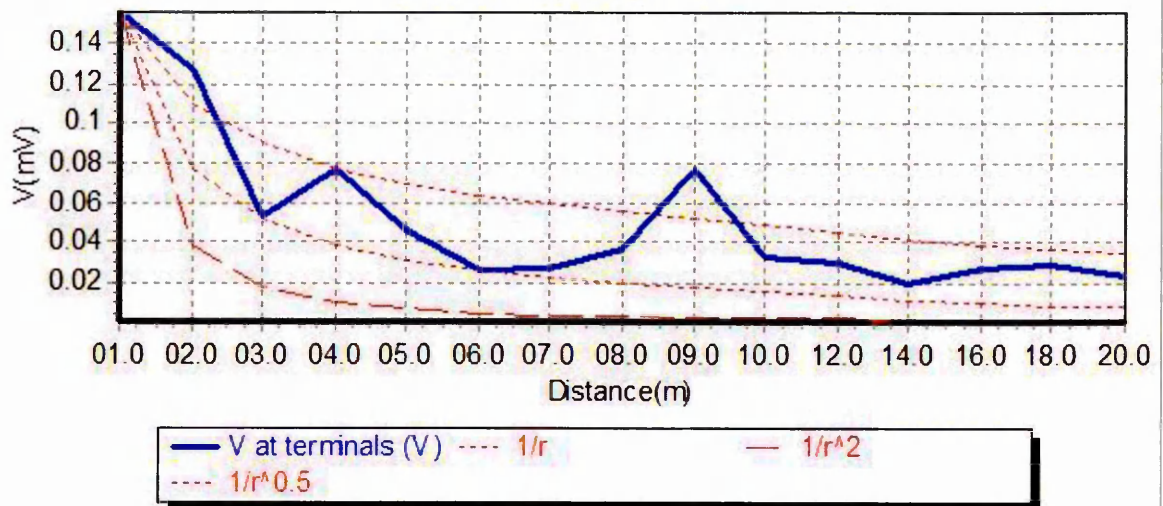
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 10,006,400 Mhz



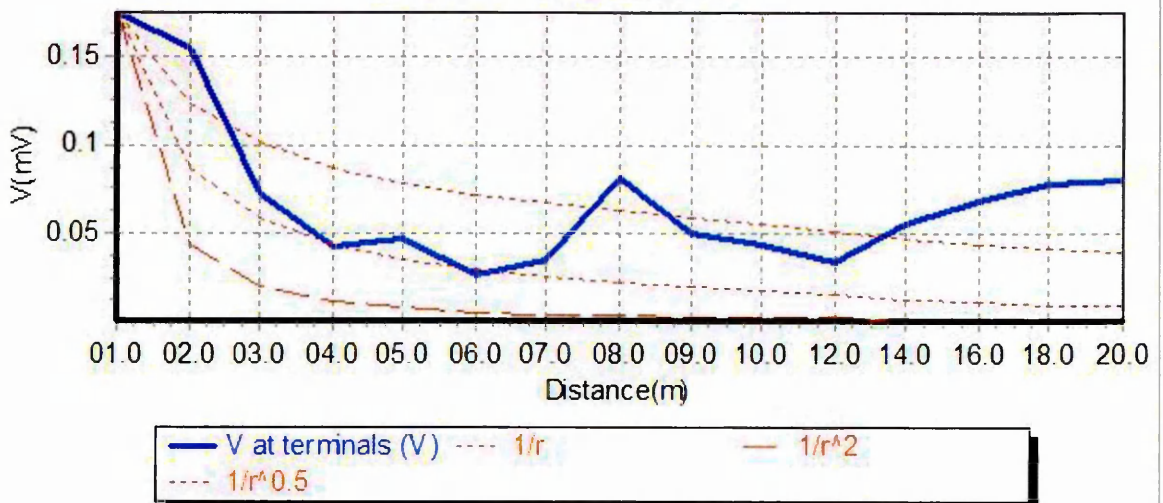
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 11,028,800 Mhz



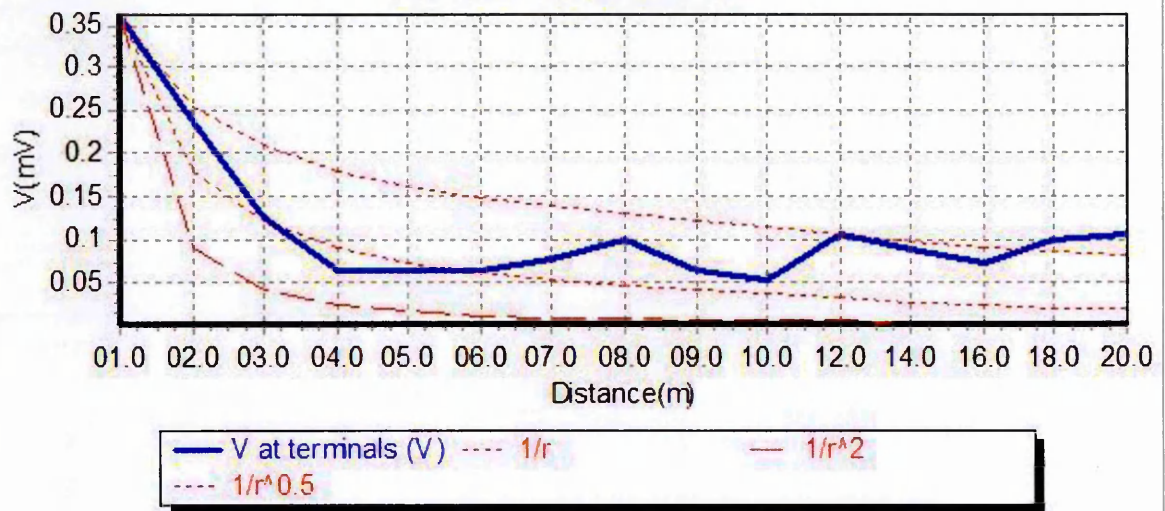
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 12,051,200 Mhz



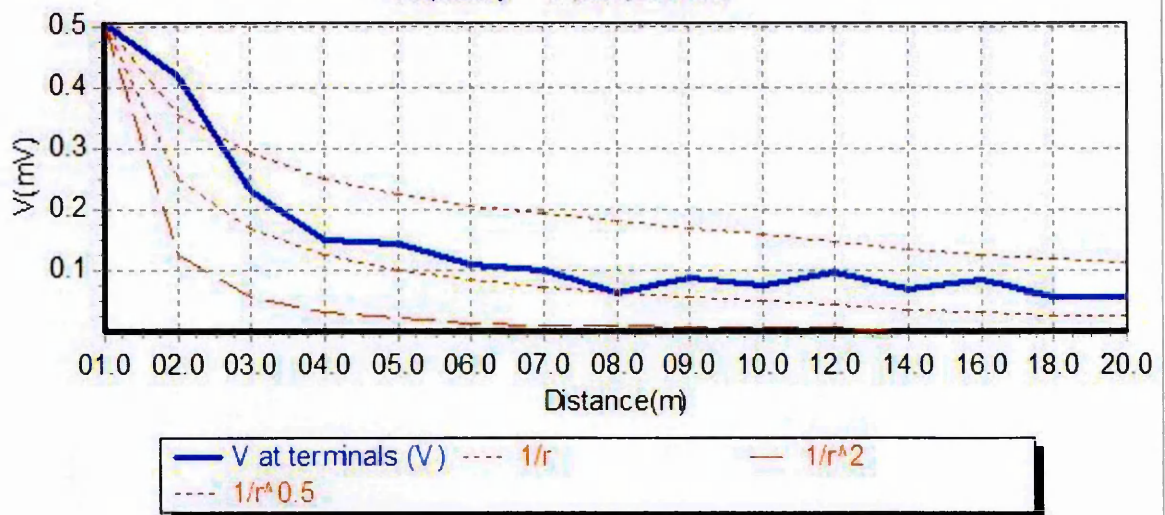
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 13,073,600 Mhz



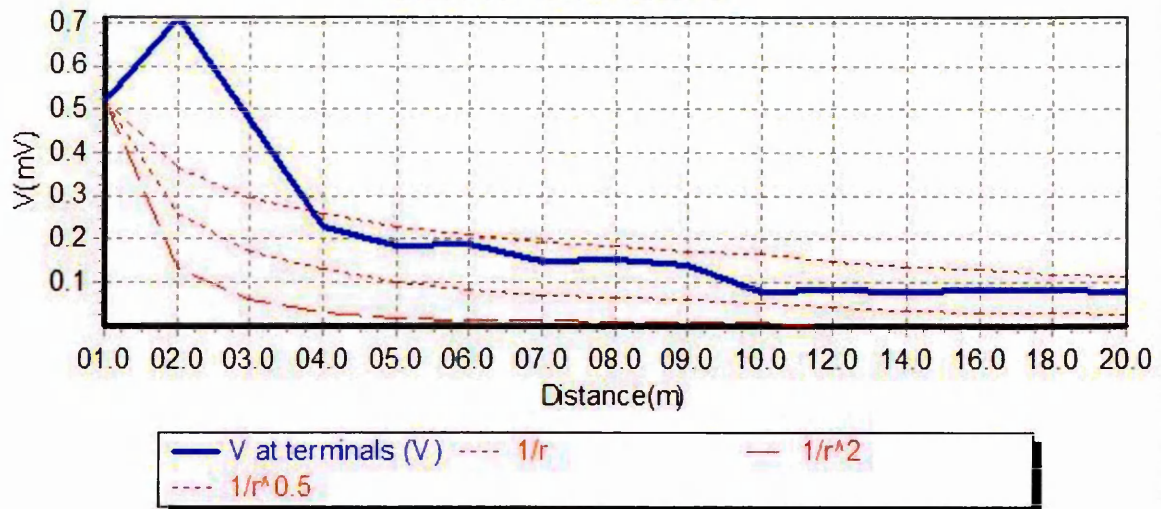
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 14,096,000 Mhz



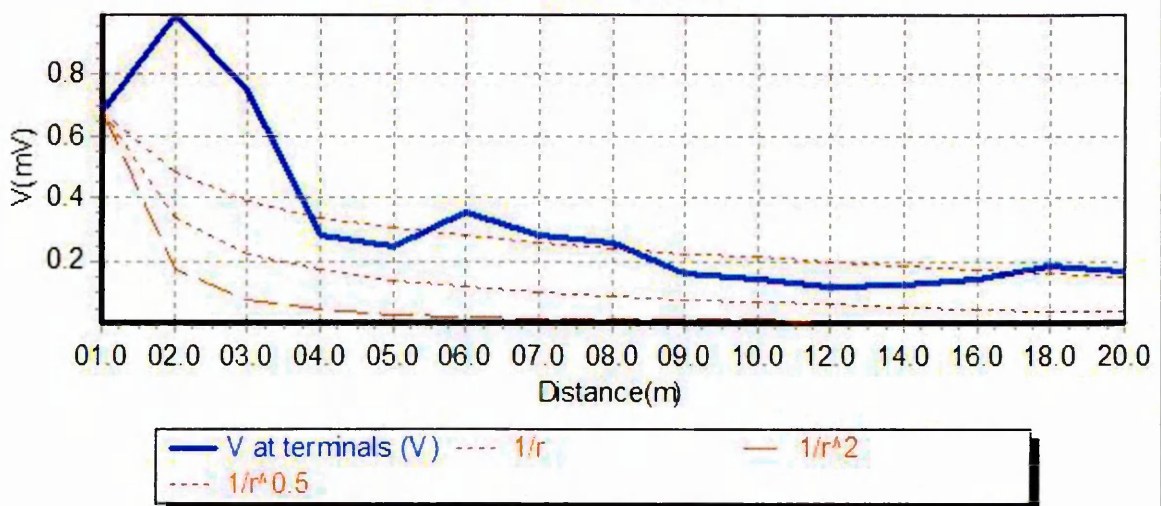
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 15,004,800 Mhz



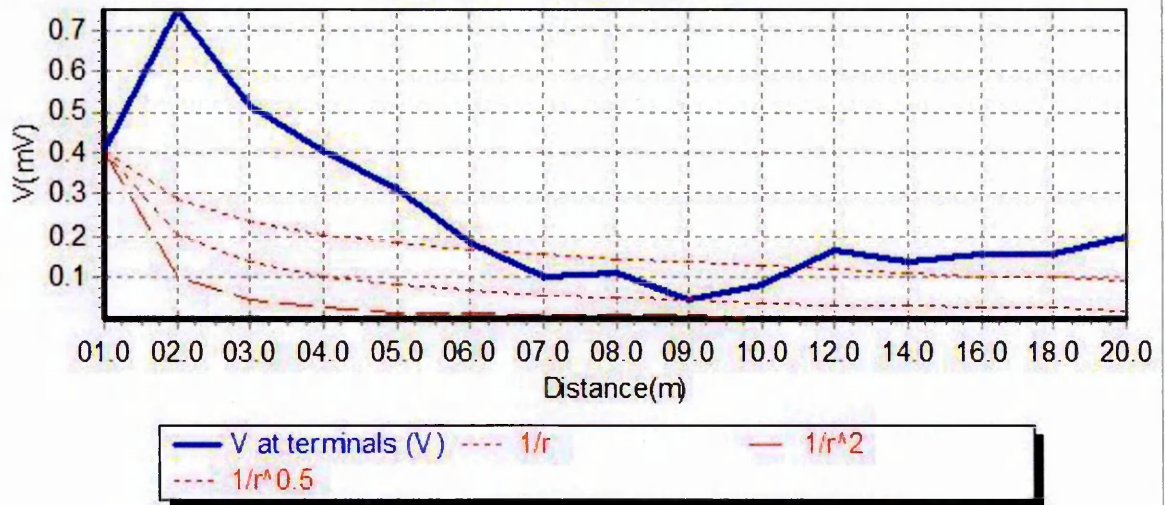
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 16,027,200 Mhz



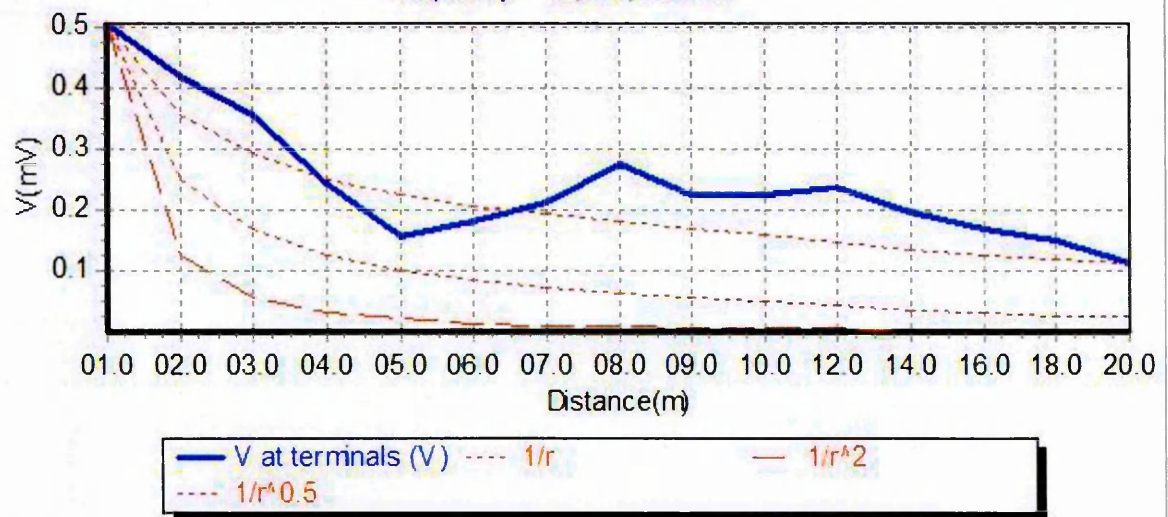
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 17,049,600 Mhz



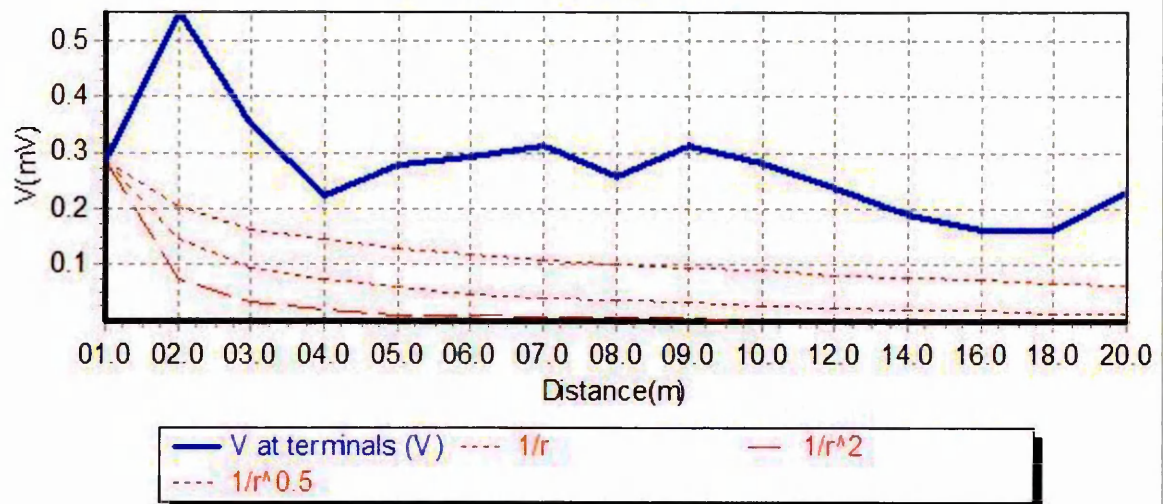
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 18,072,000 Mhz



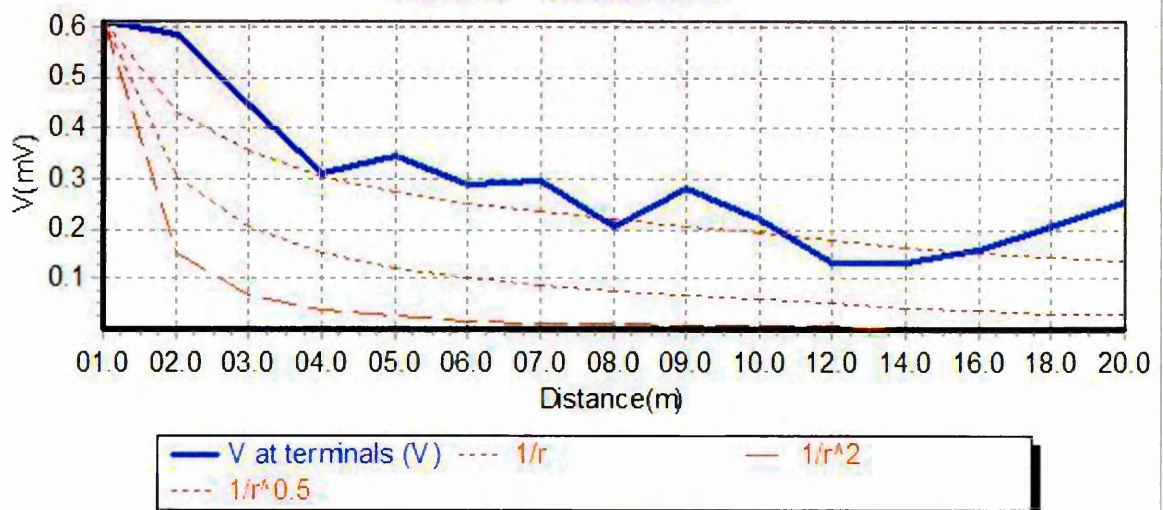
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 19,094,400 Mhz



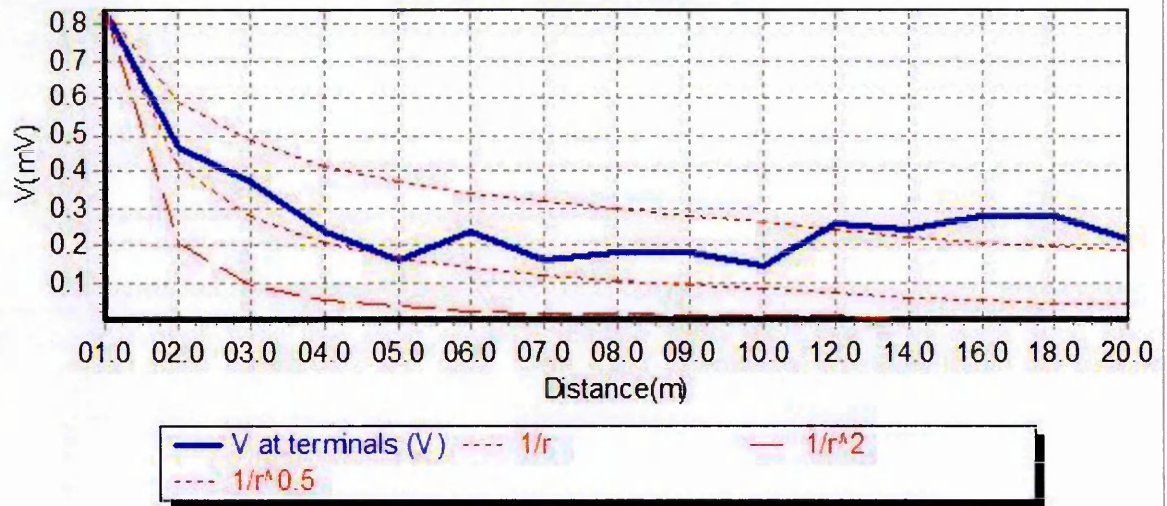
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 20,003,200 Mhz



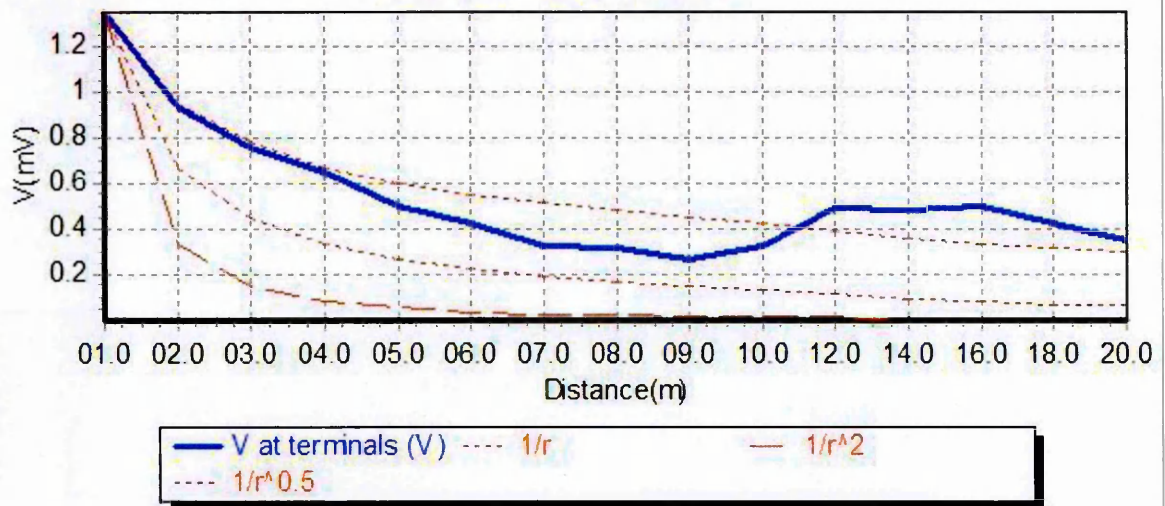
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 21,025,600 Mhz



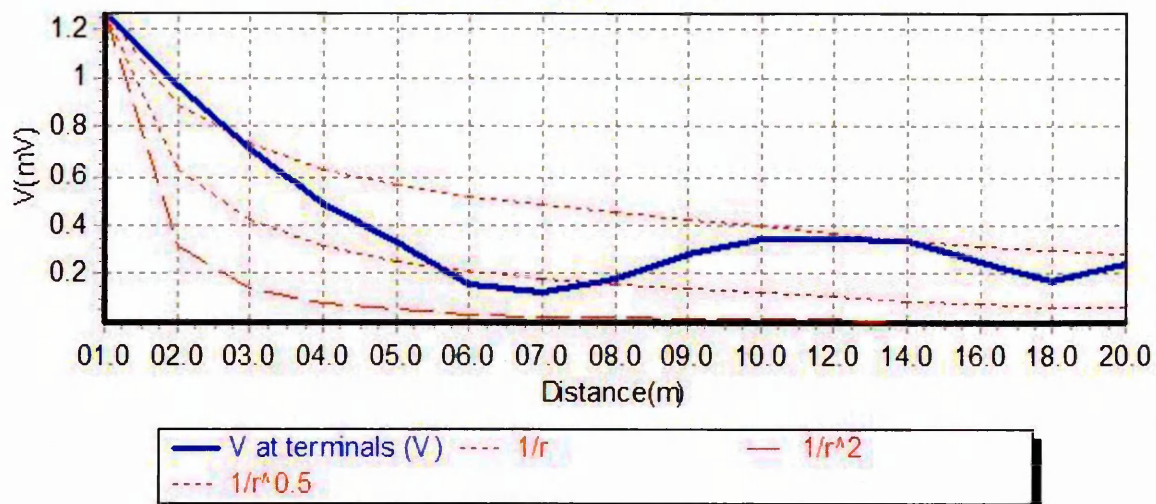
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 22,048,000 Mhz



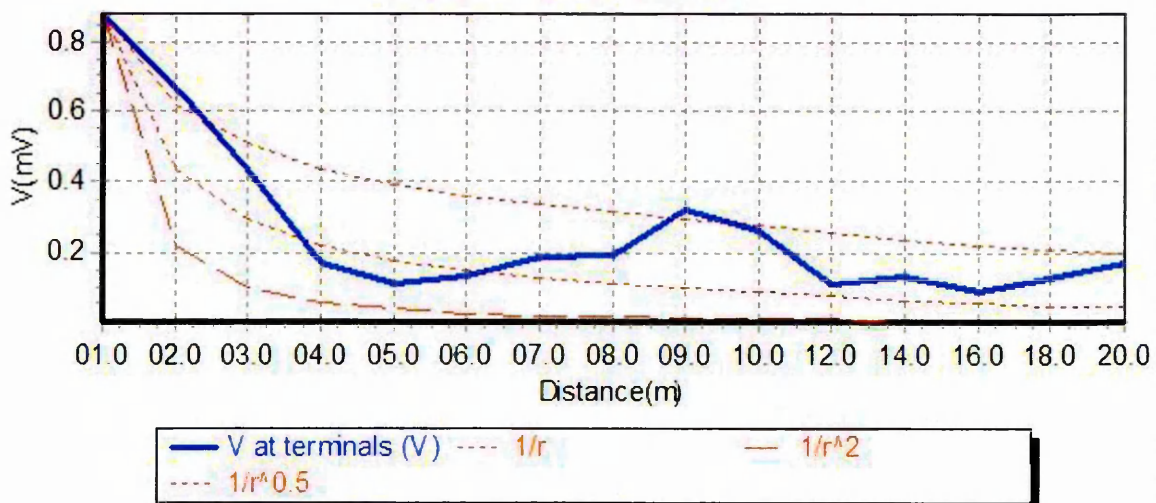
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 23,070,400 Mhz



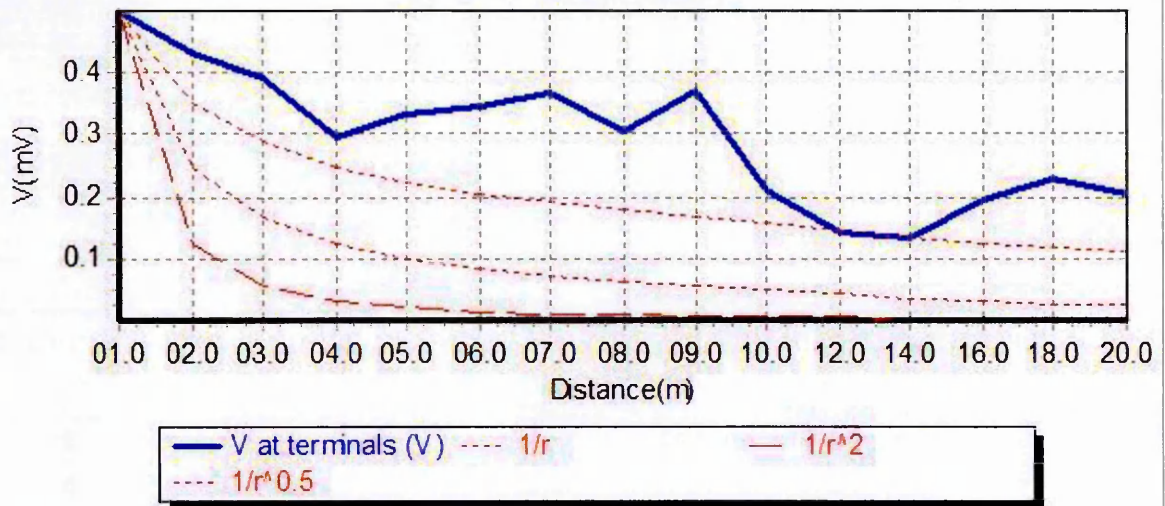
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 24,092,800 Mhz



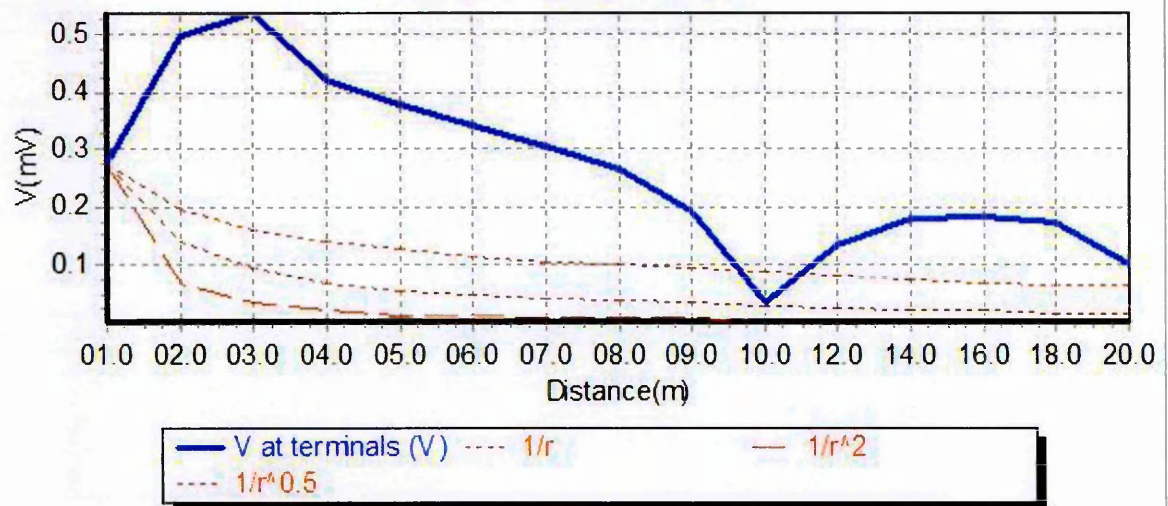
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 25,001,600 Mhz



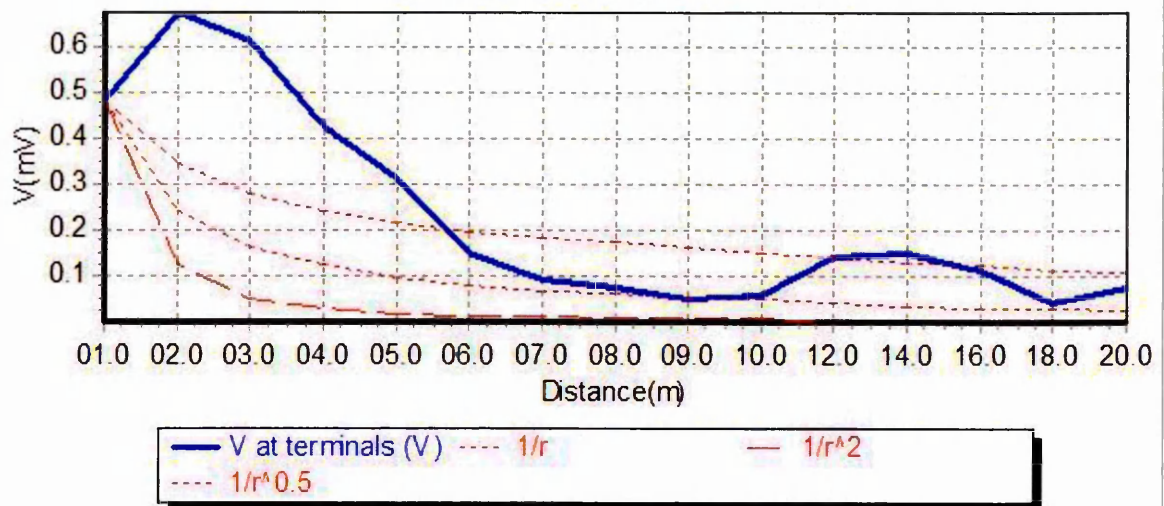
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 26,024,000 Mhz



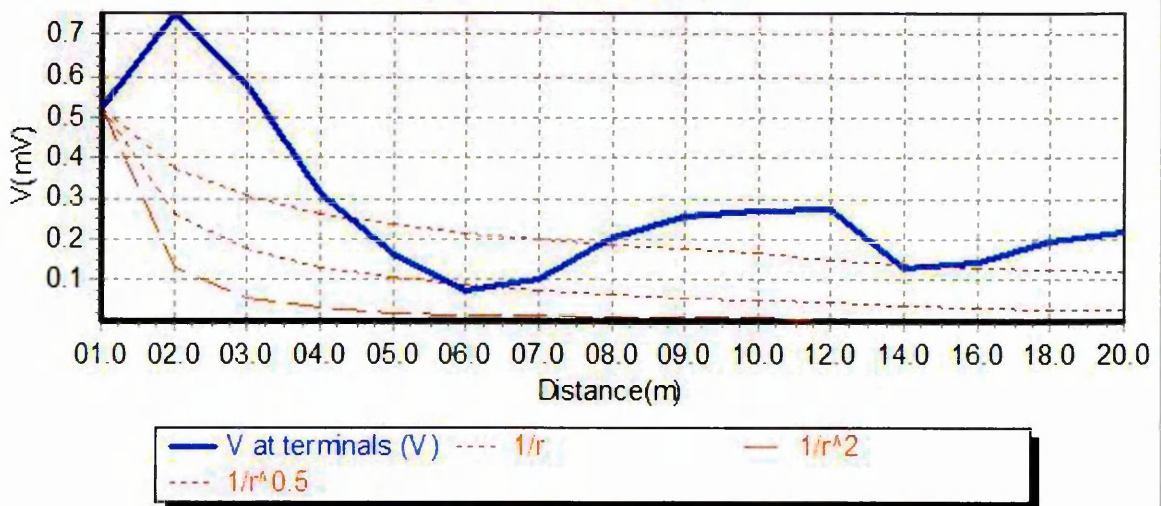
Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 27,046,400 Mhz



Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 28,068,800 Mhz

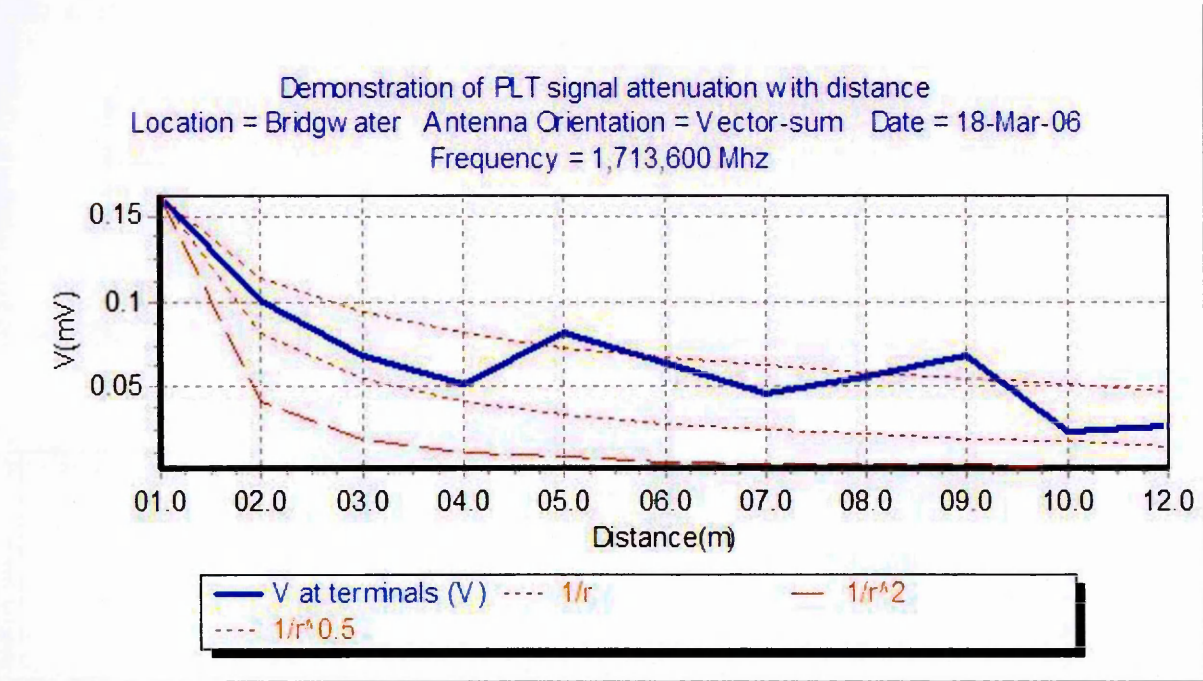


Demonstration of PLT signal attenuation with distance
 Location = Bradley Stoke Antenna Orientation = Vector-sum Date = 03-Oct-06
 Frequency = 29,091,200 Mhz

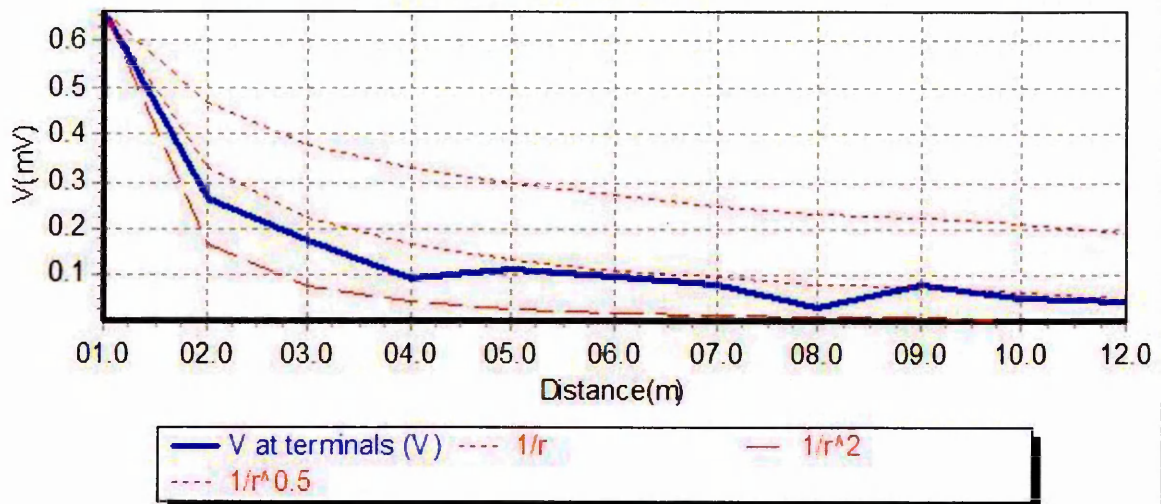


APPENDIX G: ATTENUATION WITH DISTANCE GRAPHS FOR BRIDGWATER USING ANRITSU 420B

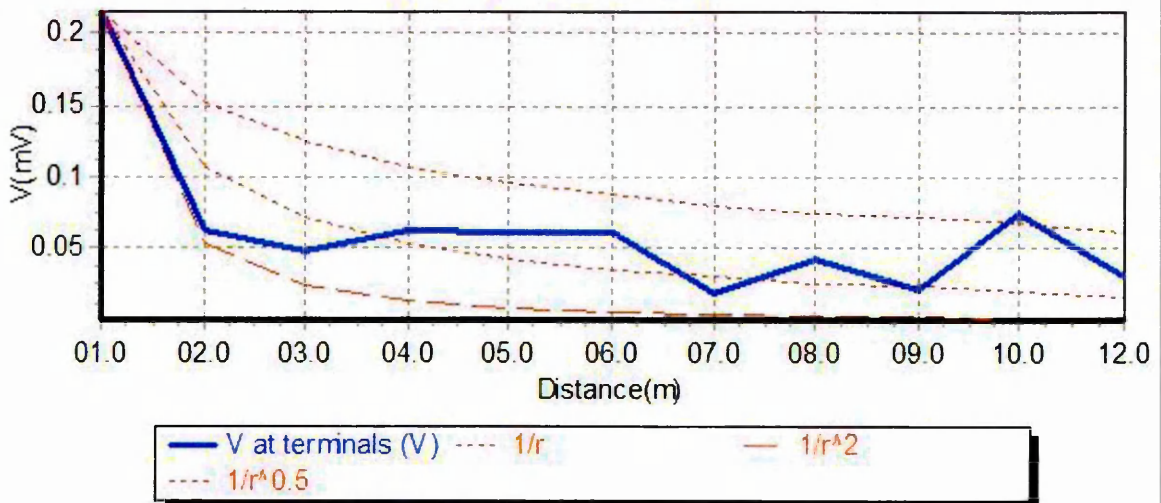
The following graphs were produced from data files produced by the Anritsu 420B network analyser during regressions measurements at Bridgwater, UK with a 0dBm injected signal. The Antenna was placed in both perpendicular and parallel orientations and the values vectorially summed. Software was written to extract 30 of the 250 frequencies and automatically populate the graphs.



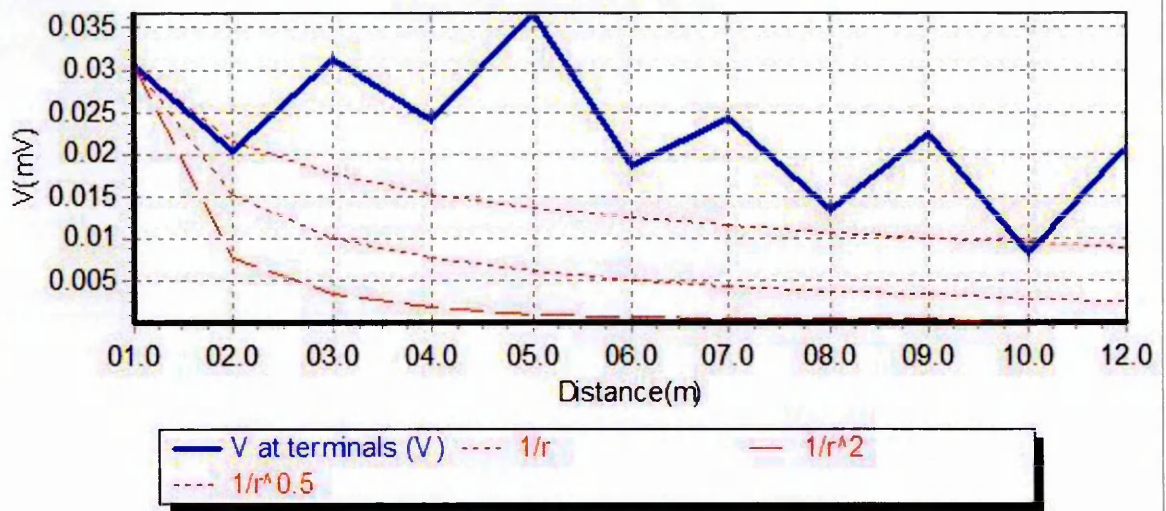
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 2,054,400 Mhz



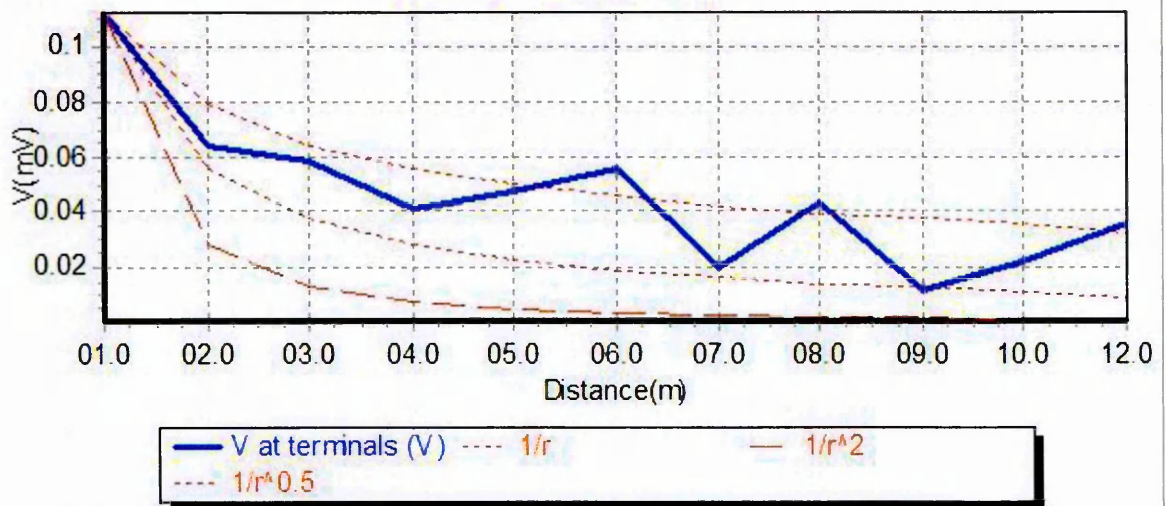
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 3,076,800 Mhz



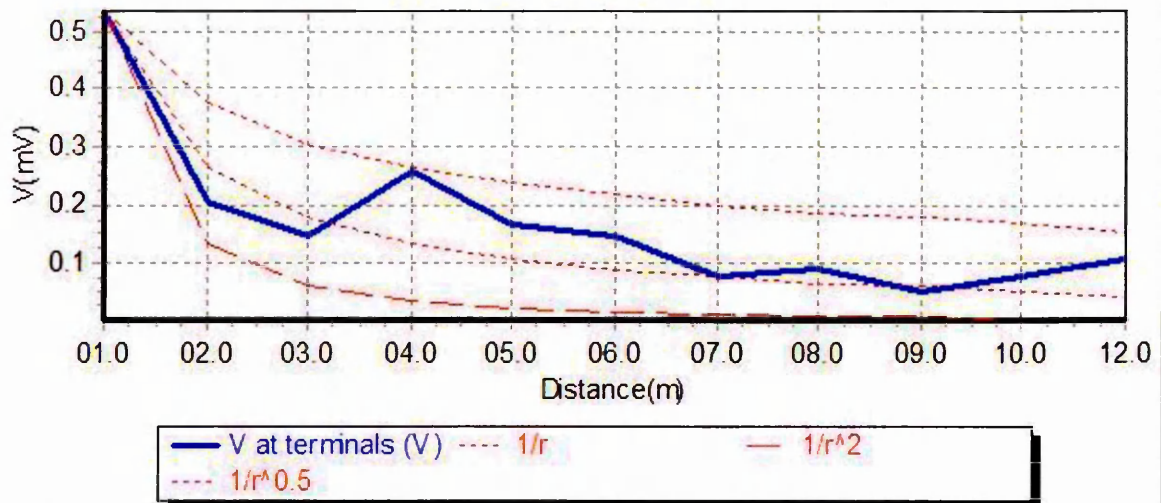
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 4,099,200 Mhz



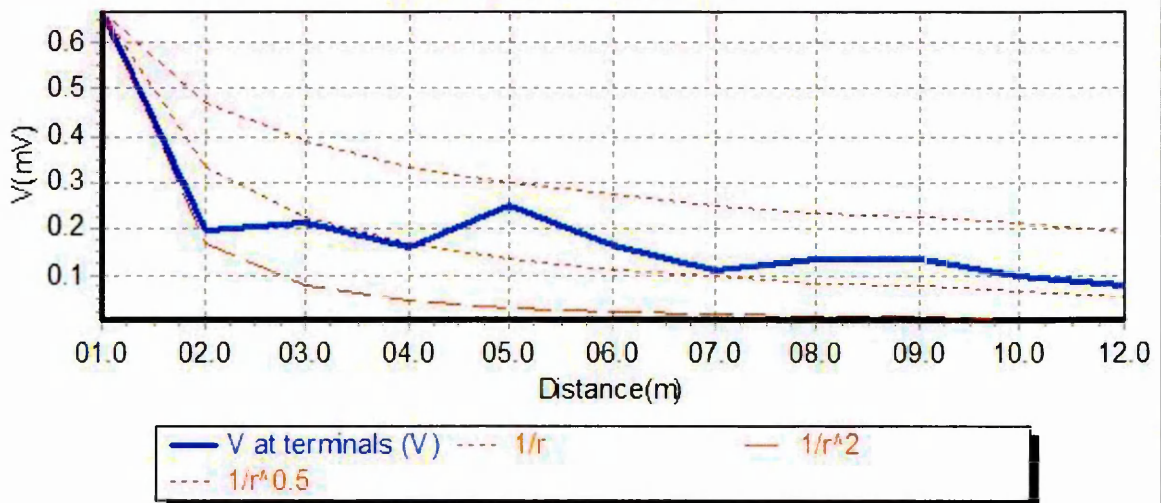
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 5,008,000 Mhz



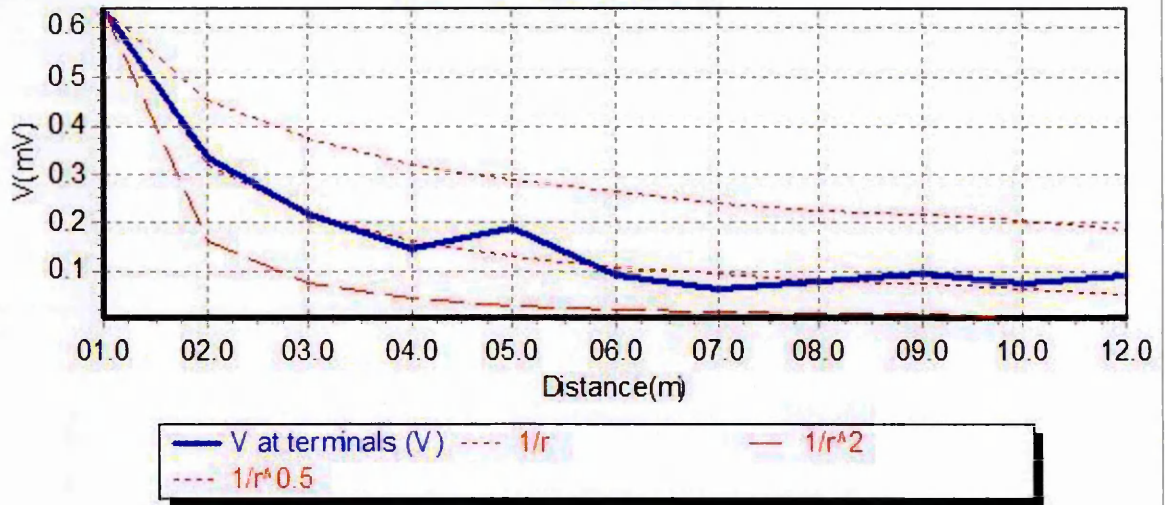
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 6,030,400 Mhz



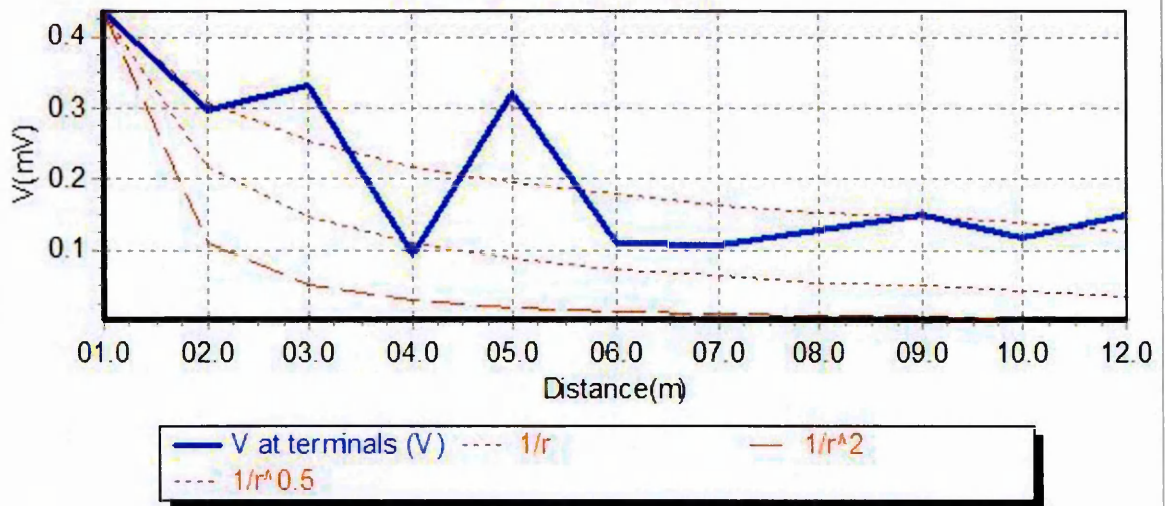
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 7,052,800 Mhz



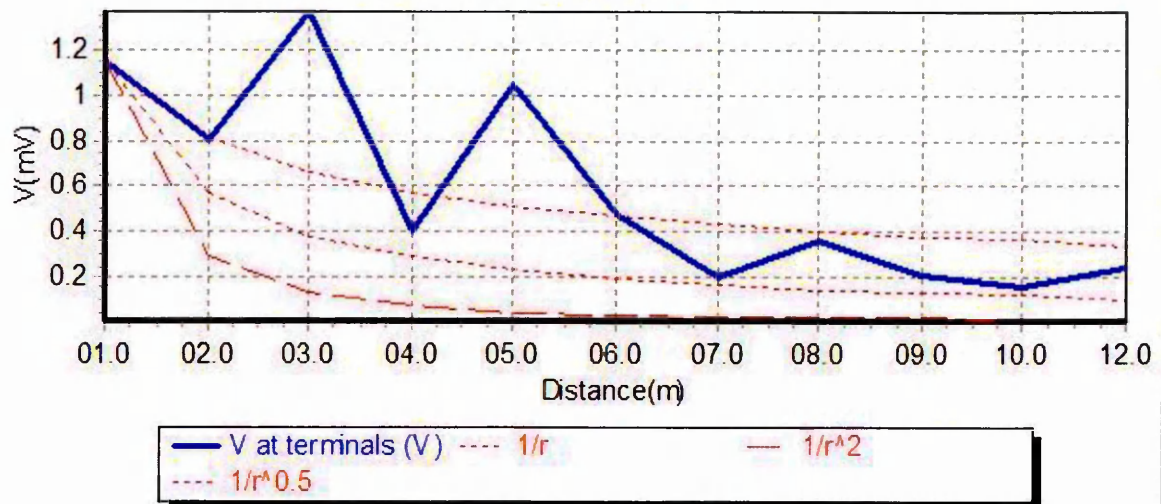
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 8,075,200 Mhz



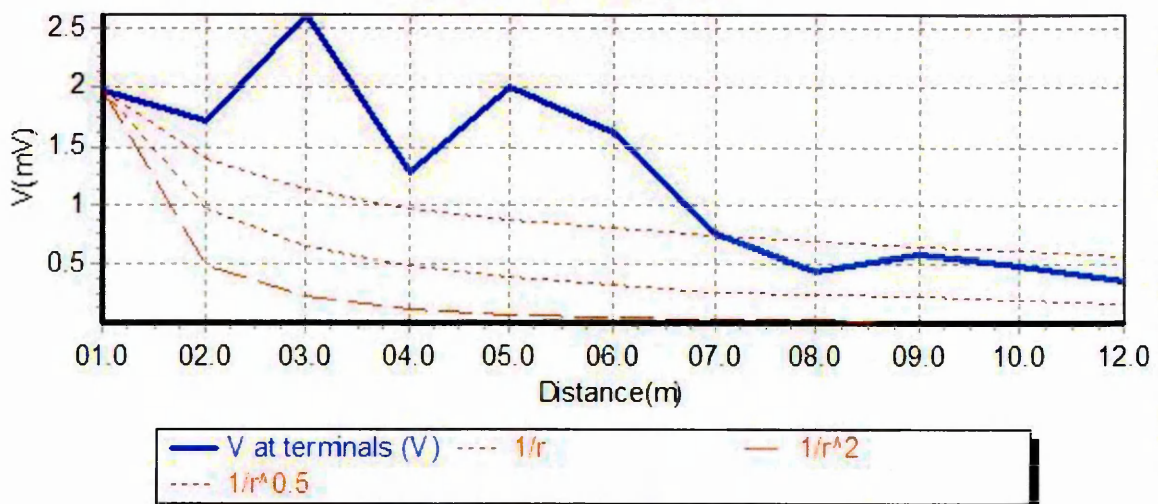
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 9,097,600 Mhz



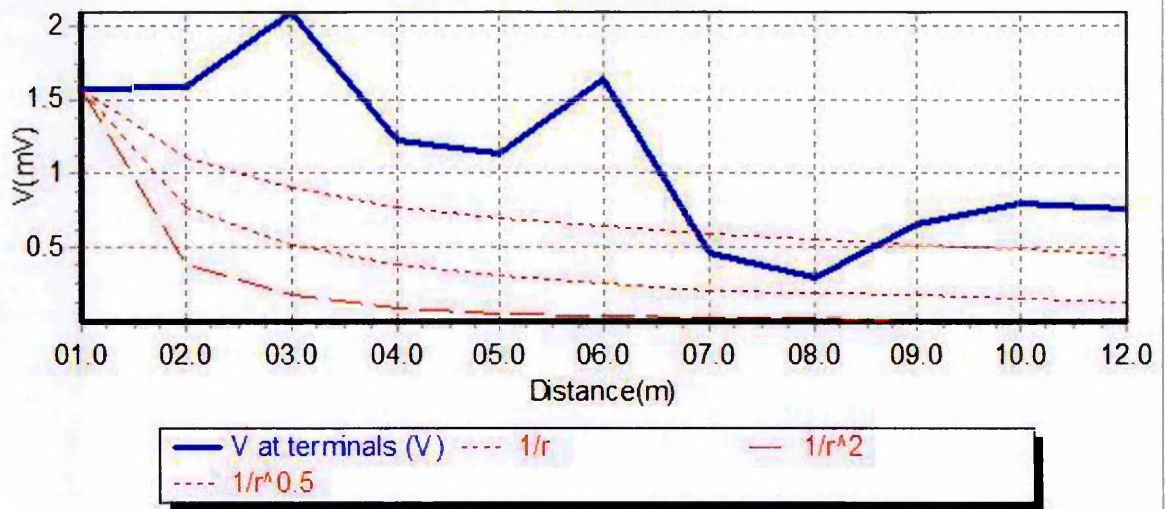
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 10,006,400 Mhz



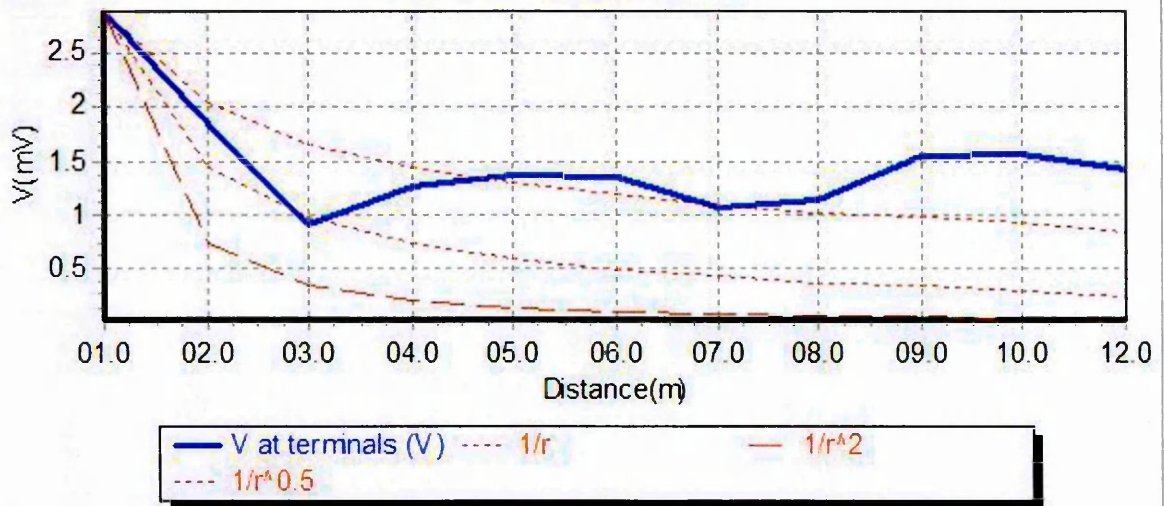
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 11,028,800 Mhz



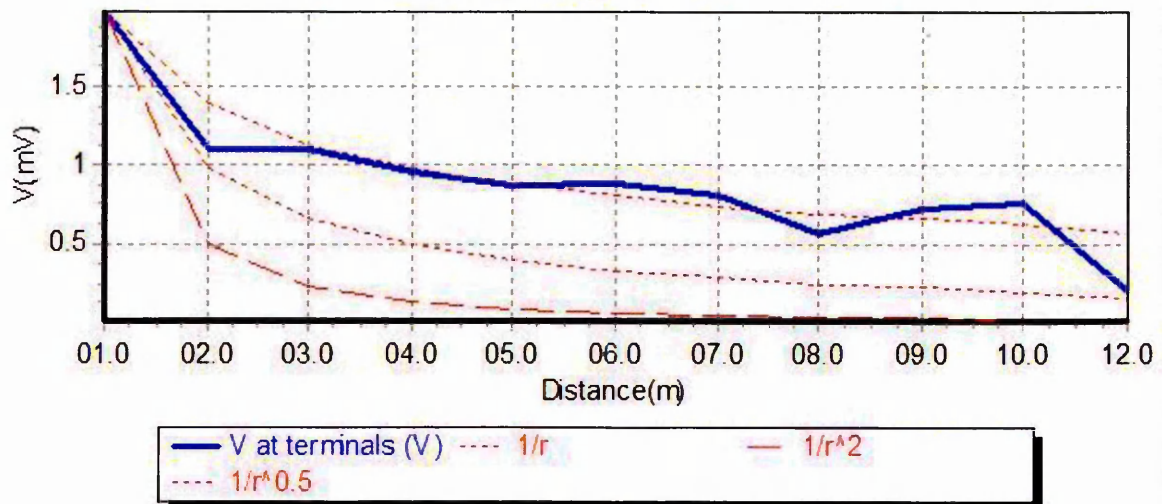
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 12,051,200 Mhz



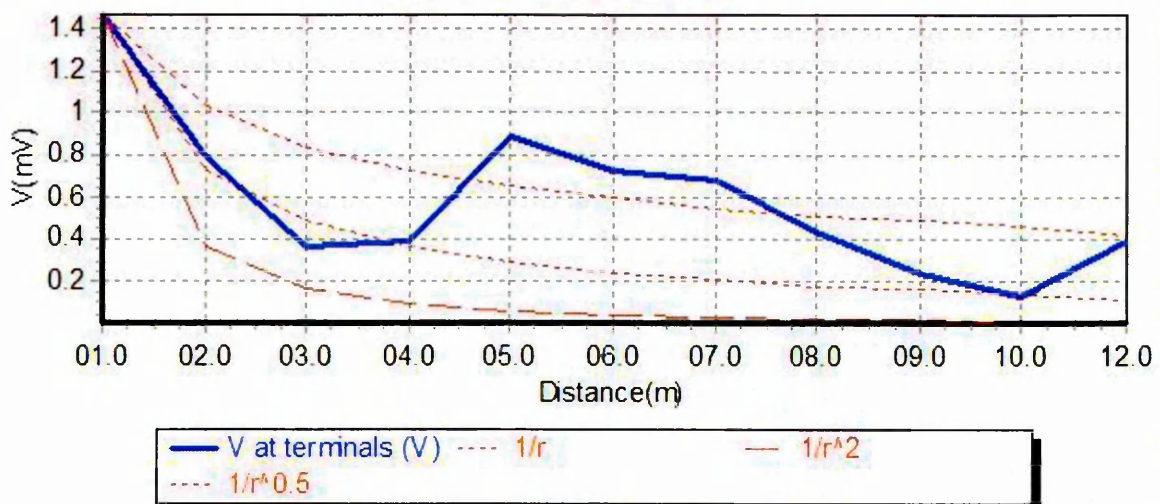
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 13,073,600 Mhz



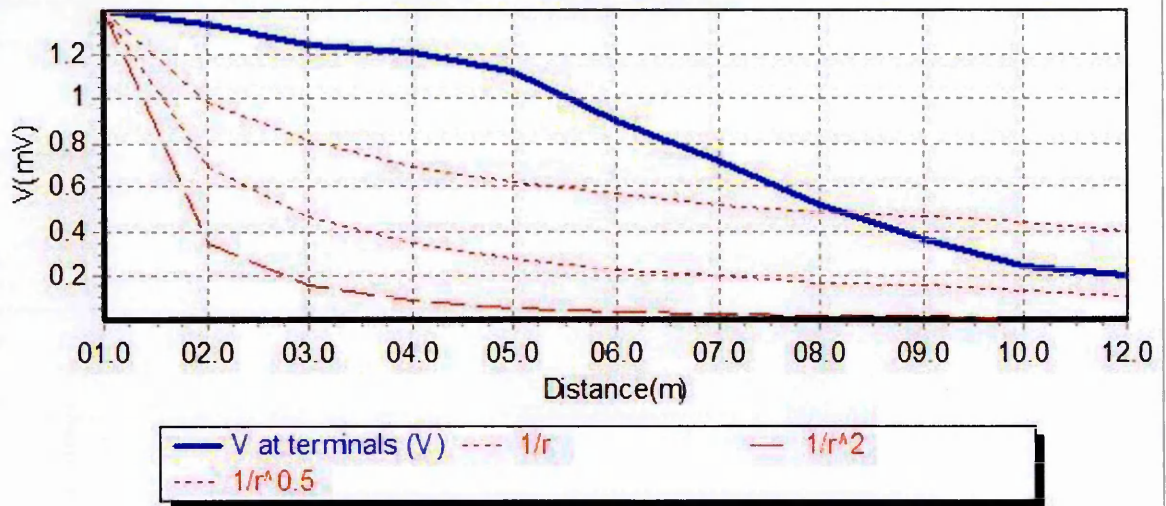
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 14,096,000 Mhz



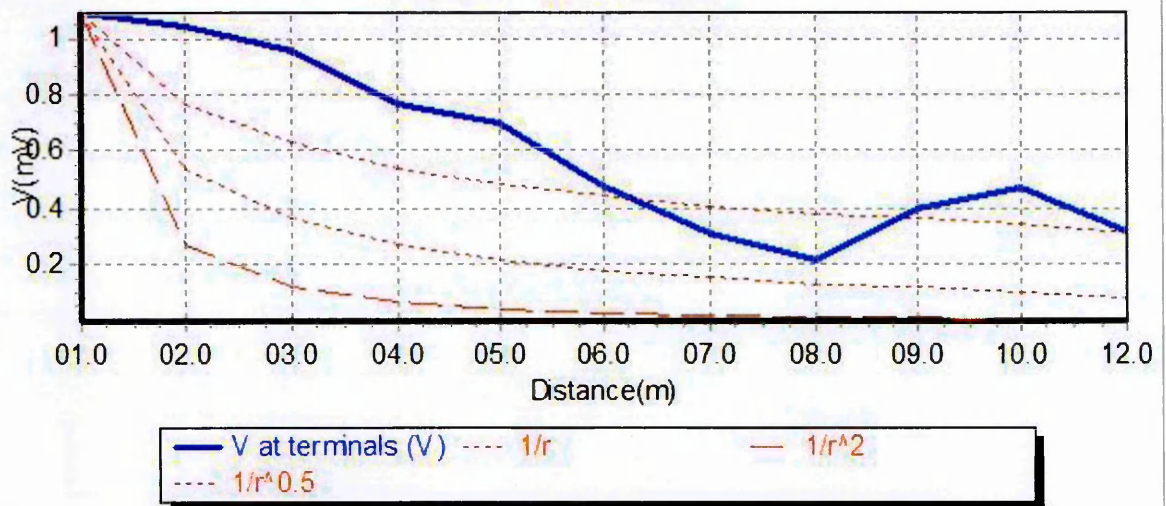
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 15,004,800 Mhz



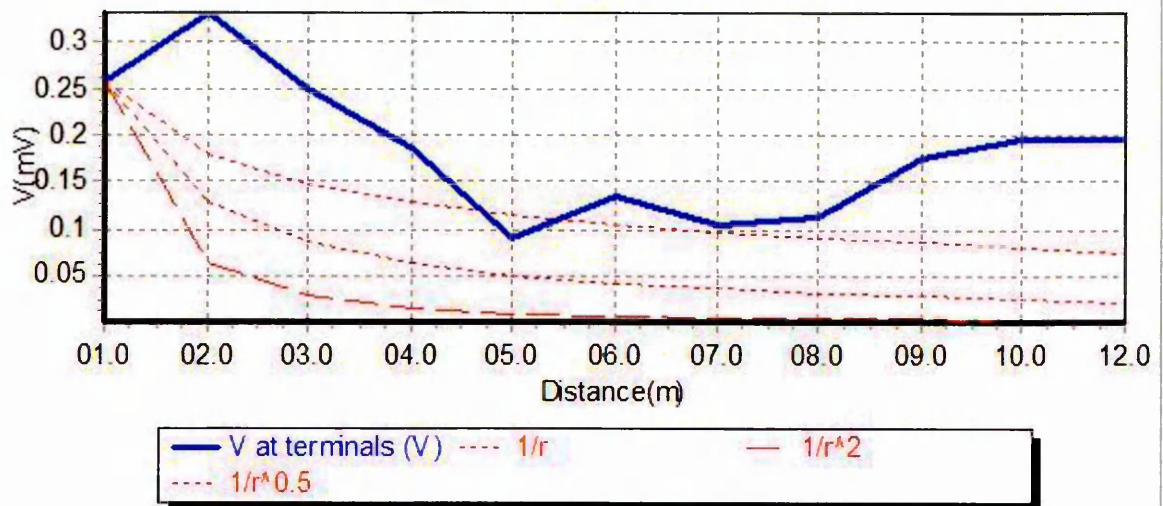
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 16,027,200 Mhz



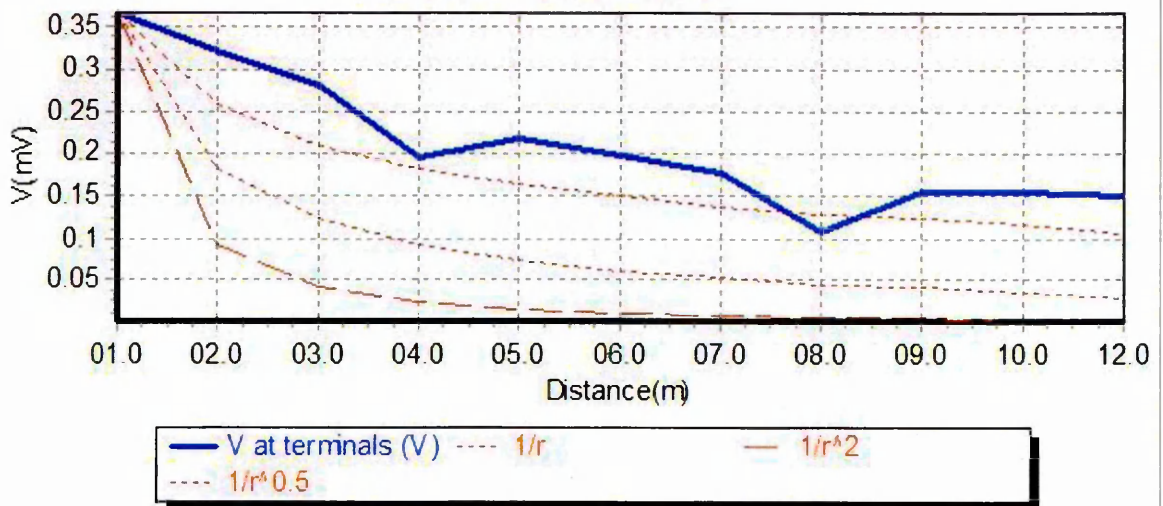
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 17,049,600 Mhz



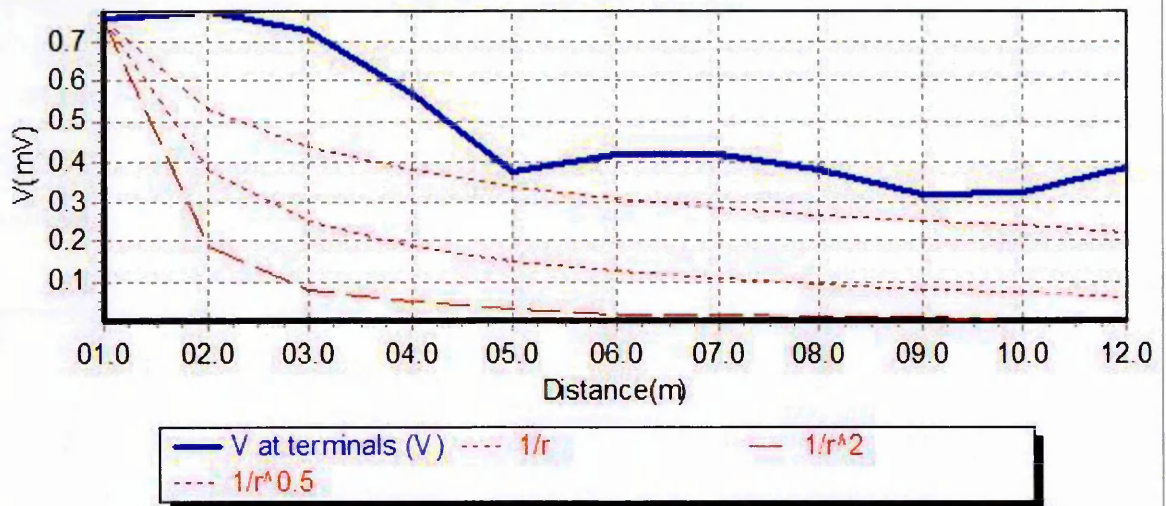
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 18,072,000 Mhz



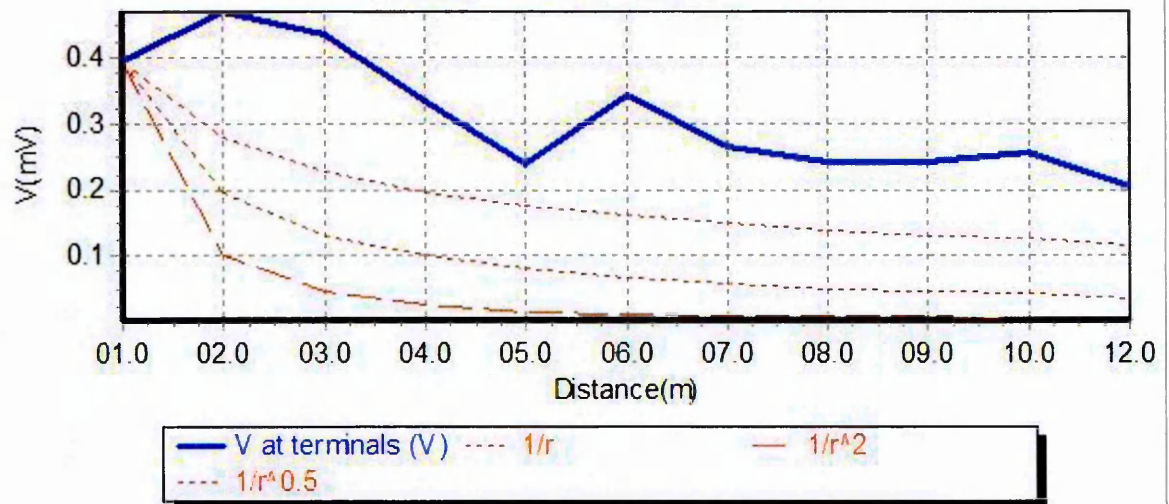
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 19,094,400 Mhz



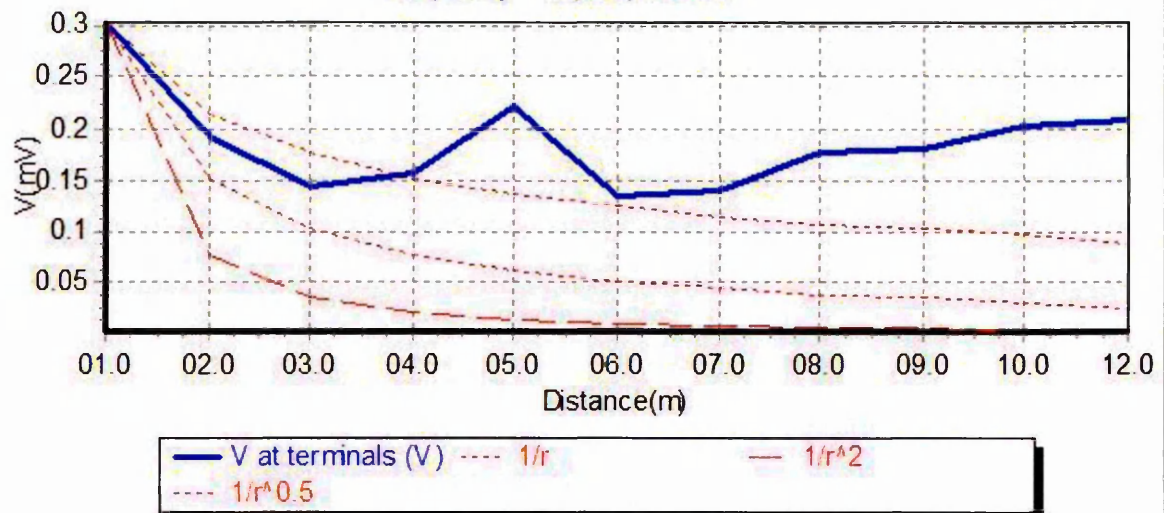
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 20,003,200 Mhz



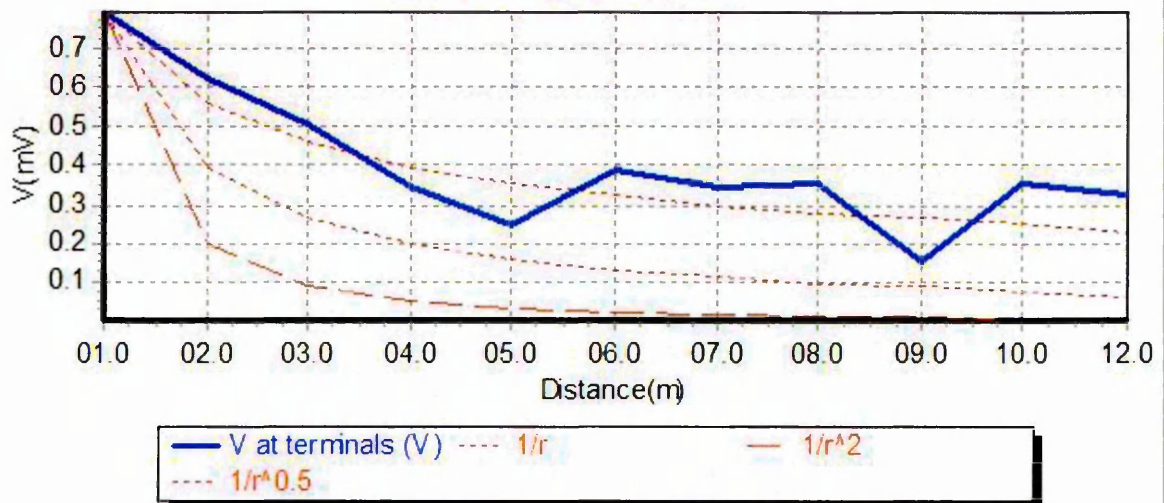
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 21,025,600 Mhz



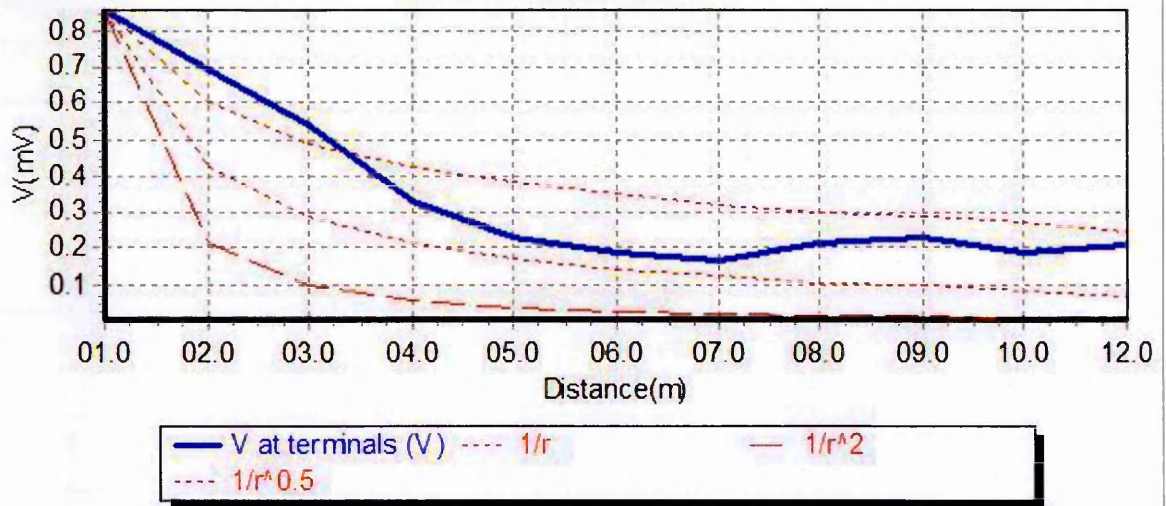
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 22,048,000 Mhz



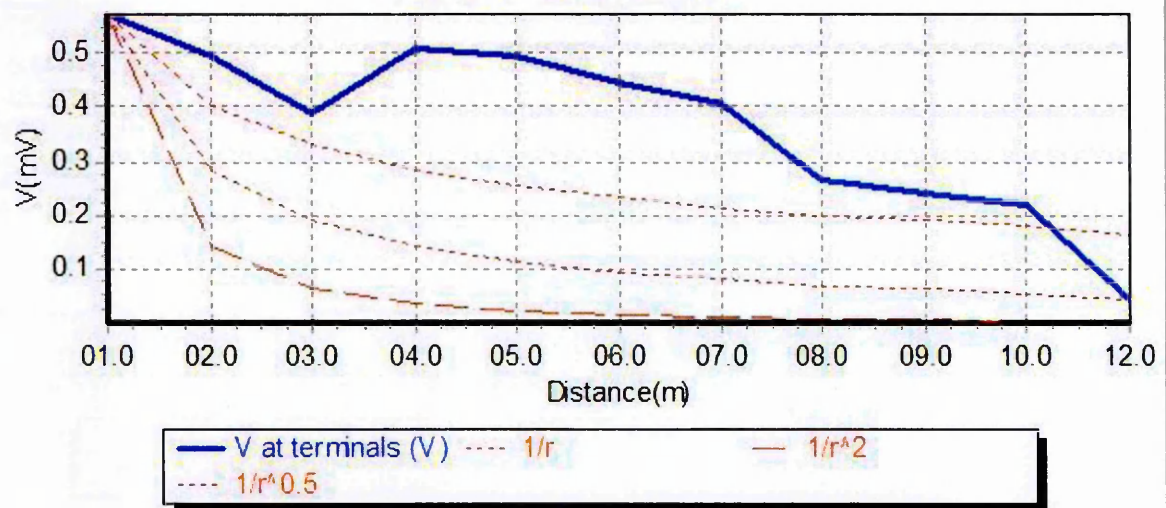
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 23,070,400 Mhz



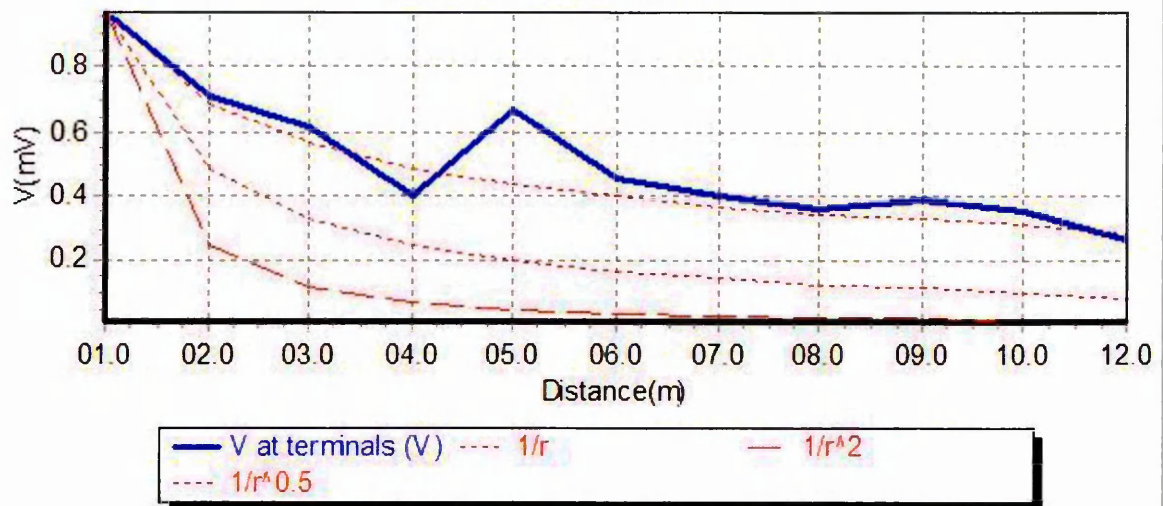
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 24,092,800 Mhz



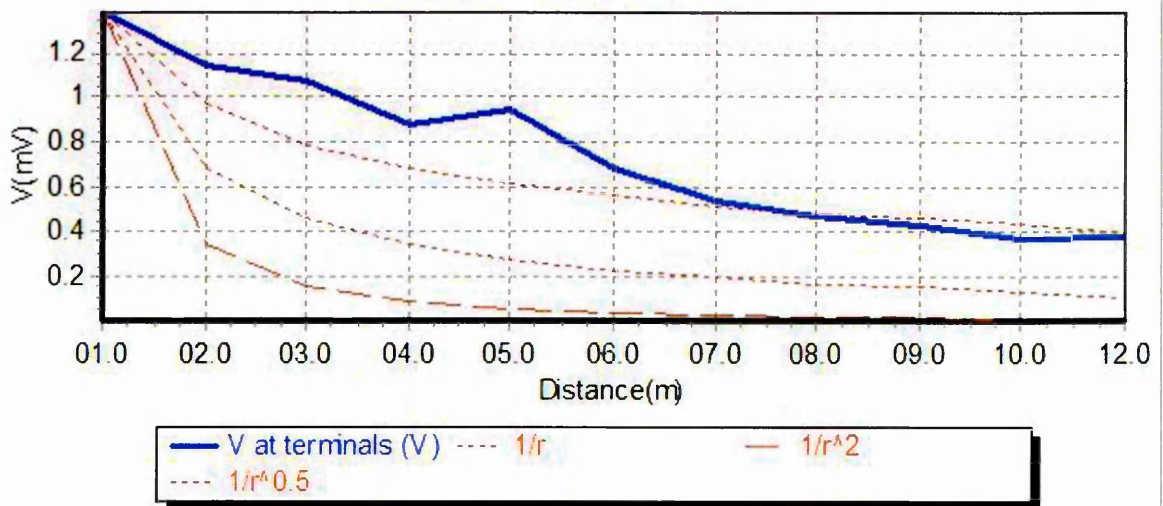
Demonstration of PLT signal attenuation with distance
 Location = Bridgw ater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 25,001,600 Mhz



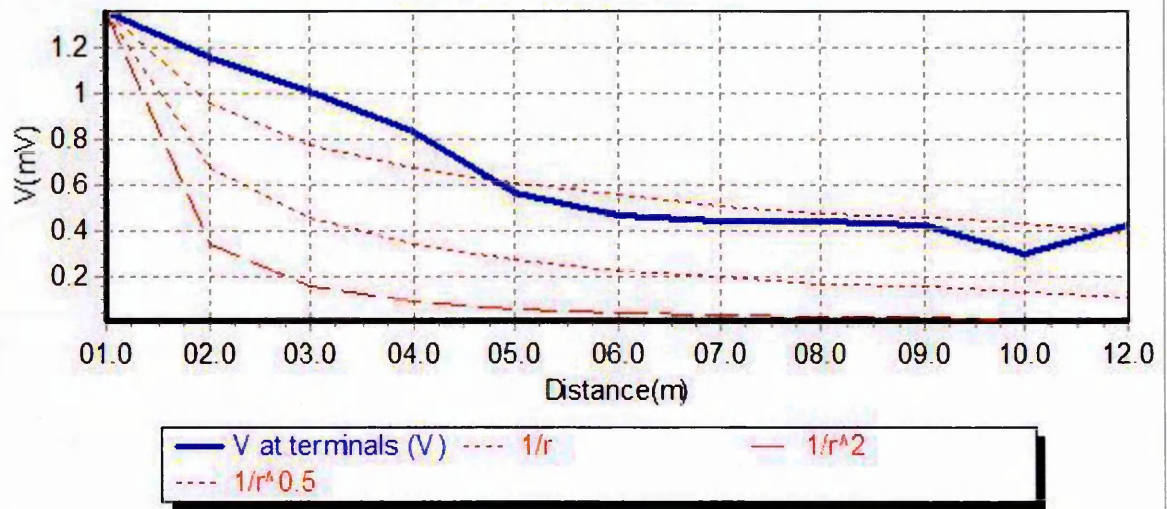
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 26,024,000 Mhz



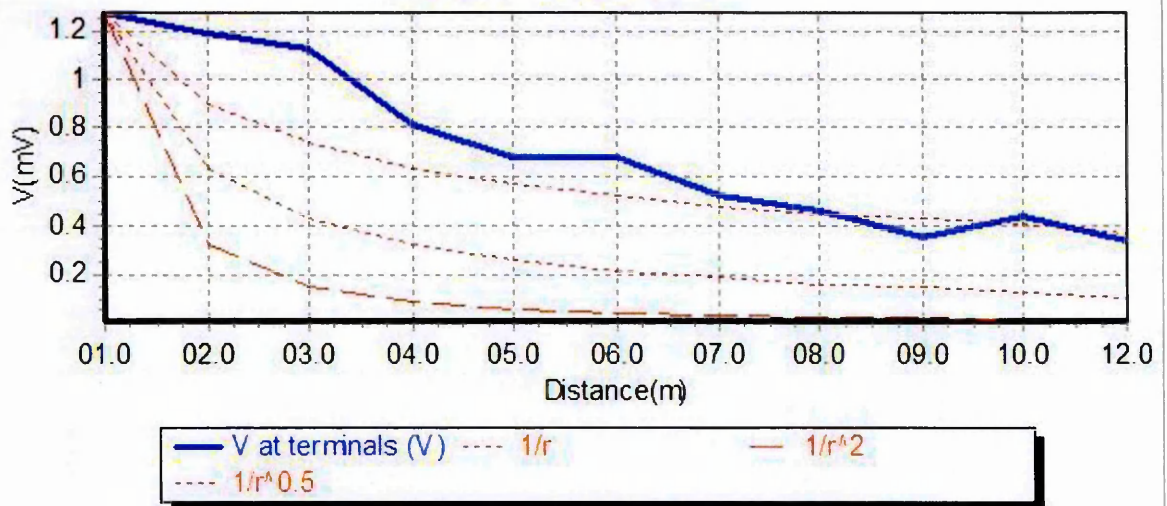
Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 27,046,400 Mhz



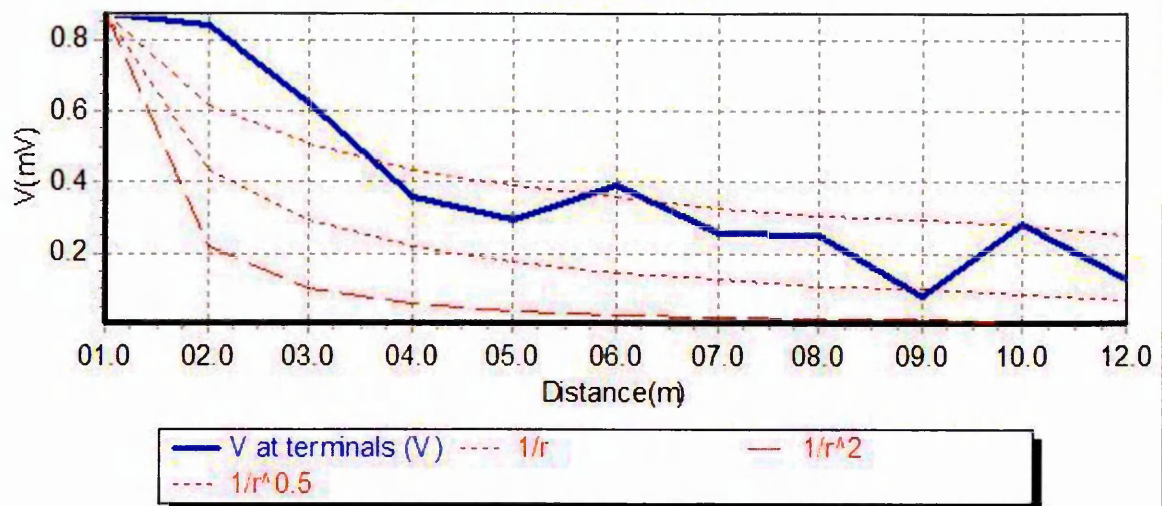
Demonstration of PLT signal attenuation with distance
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 Frequency = 28,068,800 Mhz



Demonstration of PLT signal attenuation with distance
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 Frequency = 29,091,200 Mhz

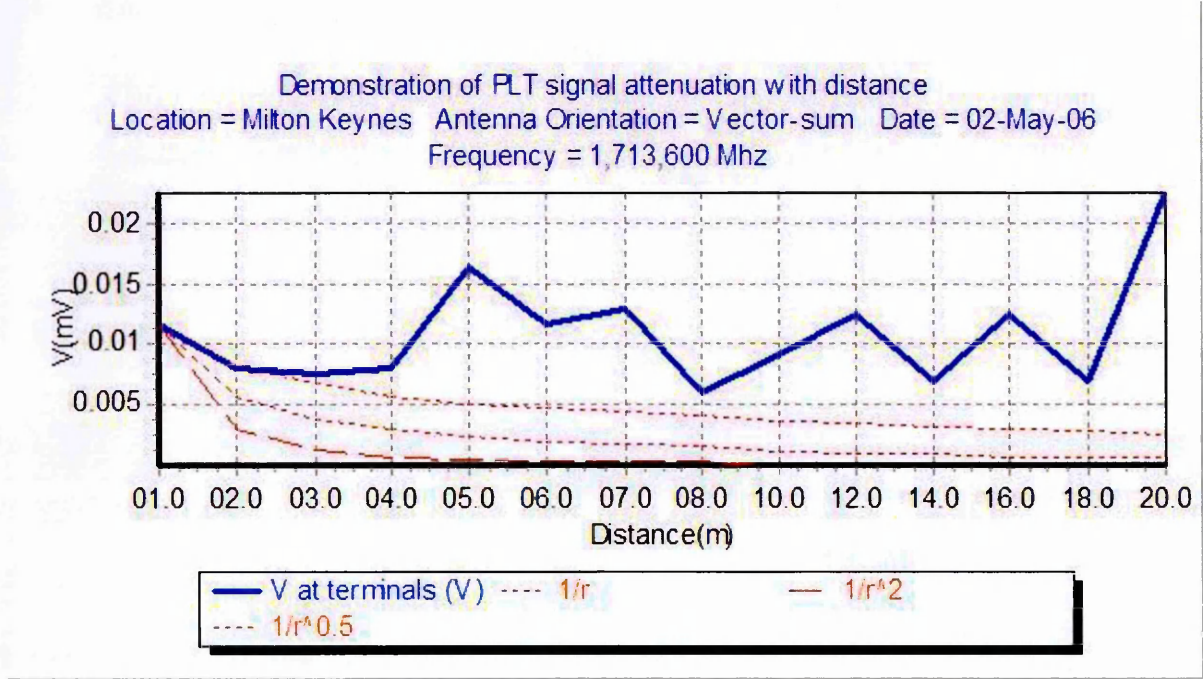


Demonstration of PLT signal attenuation with distance
 Location = Bridgwater Antenna Orientation = Vector-sum Date = 18-Mar-06
 Frequency = 30,000,000 Mhz

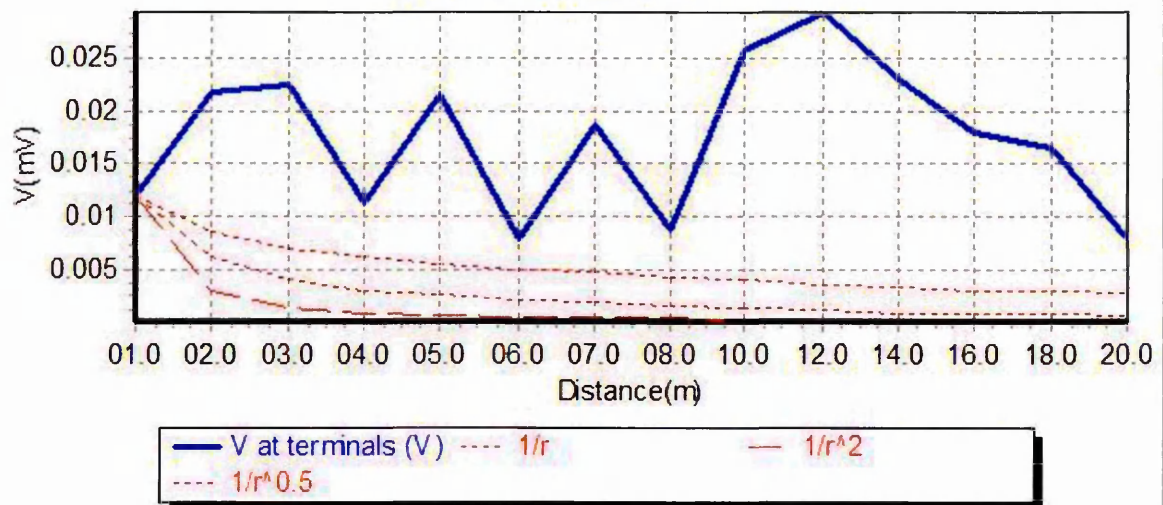


APPENDIX H: ATTENUATION WITH DISTANCE GRAPHS FOR MILTON KEYNES
USING ANRITSU 420B

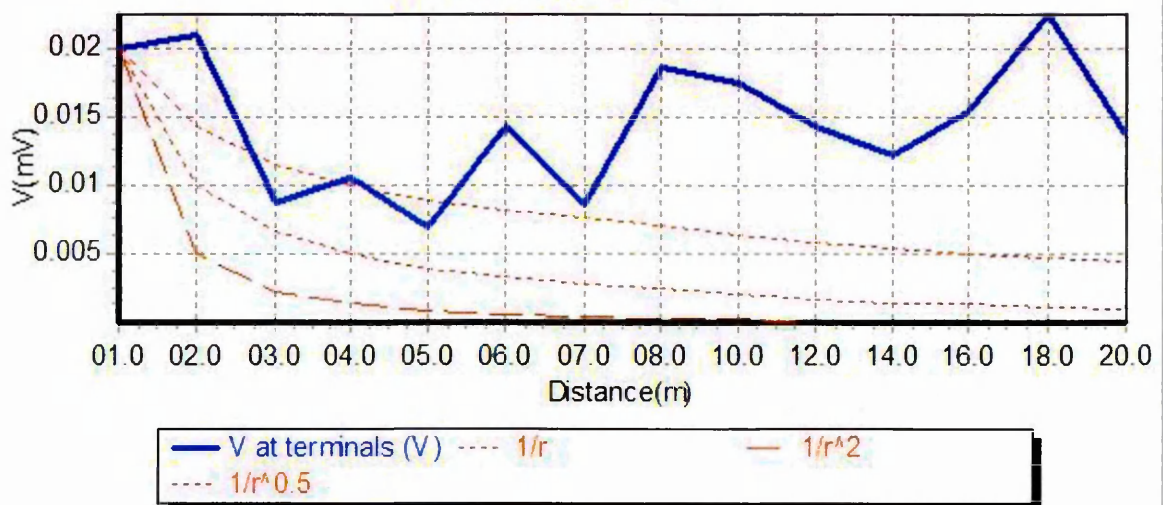
The following graphs were produced from data files produced by the Anritsu 420B network analyser during regressions measurements at Milton Keynes, UK with a 0dBm injected signal. The Antenna was placed in both perpendicular and parallel orientations and the values vectorially summed. Software was written to extract 30 of the 250 frequencies and automatically populate the graphs.



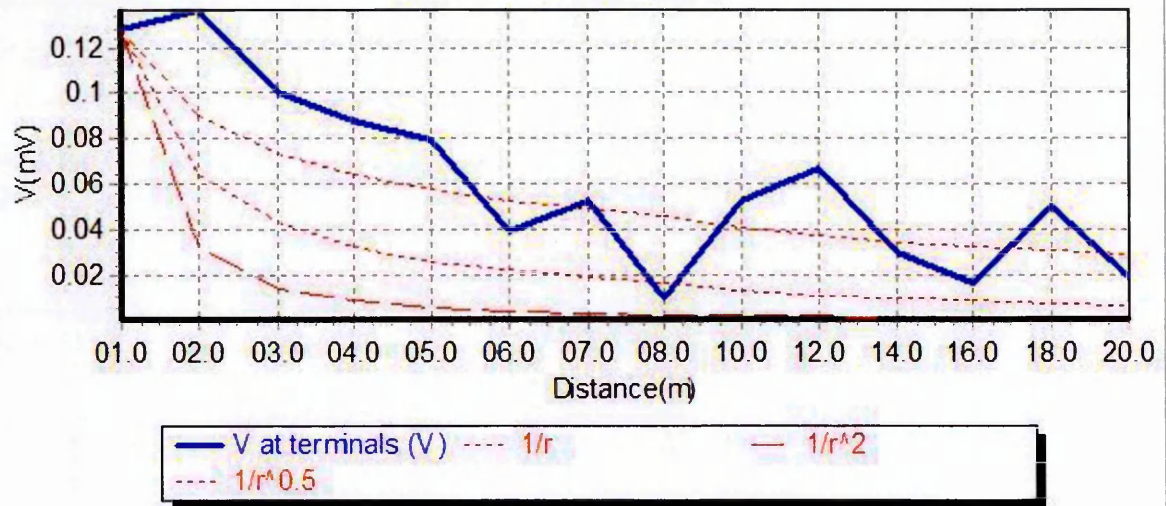
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 2,054,400 Mhz



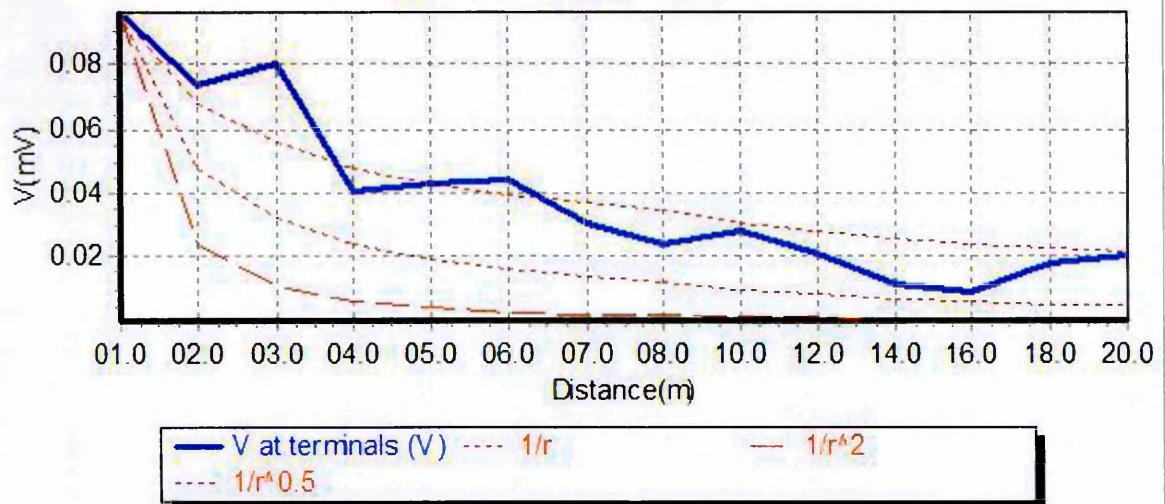
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 3,076,800 Mhz



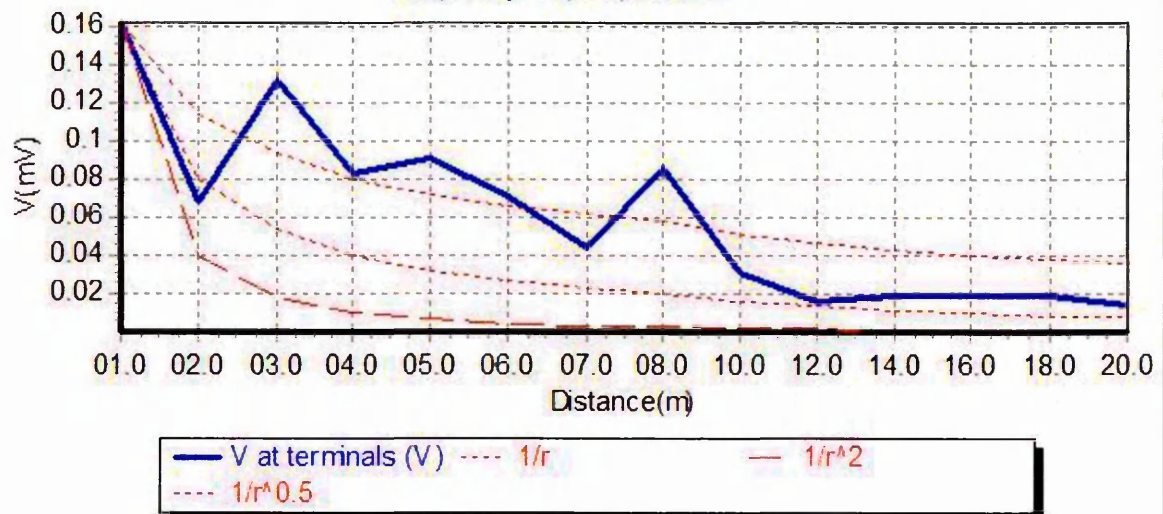
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 4,099,200 Mhz



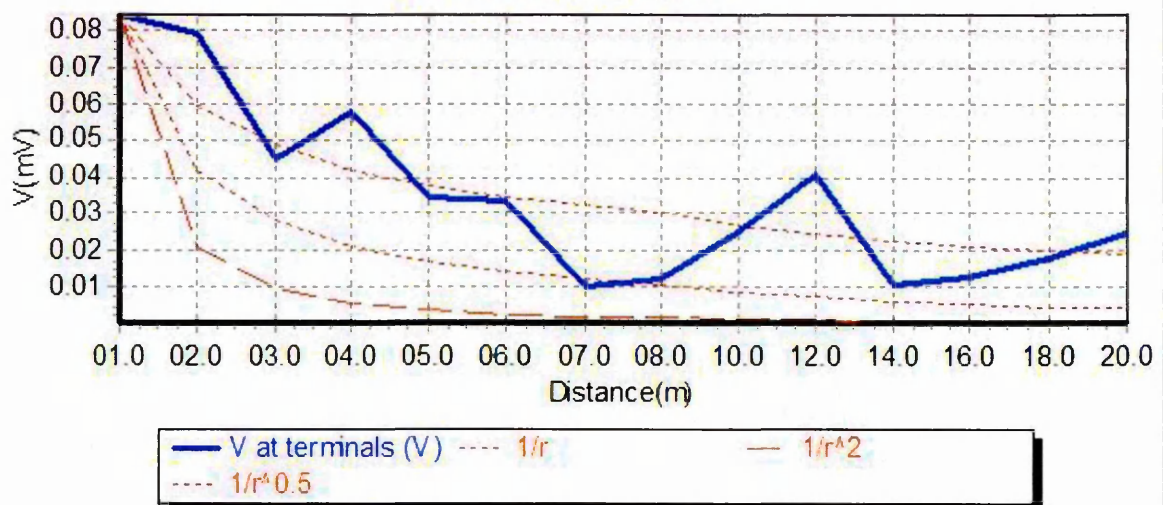
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 5,008,000 Mhz



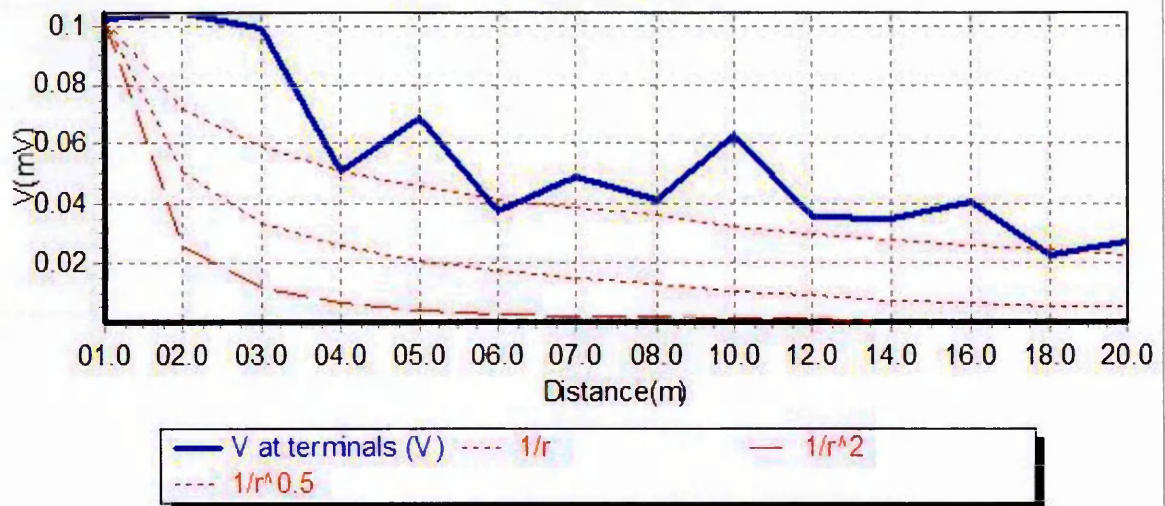
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 6,030,400 Mhz



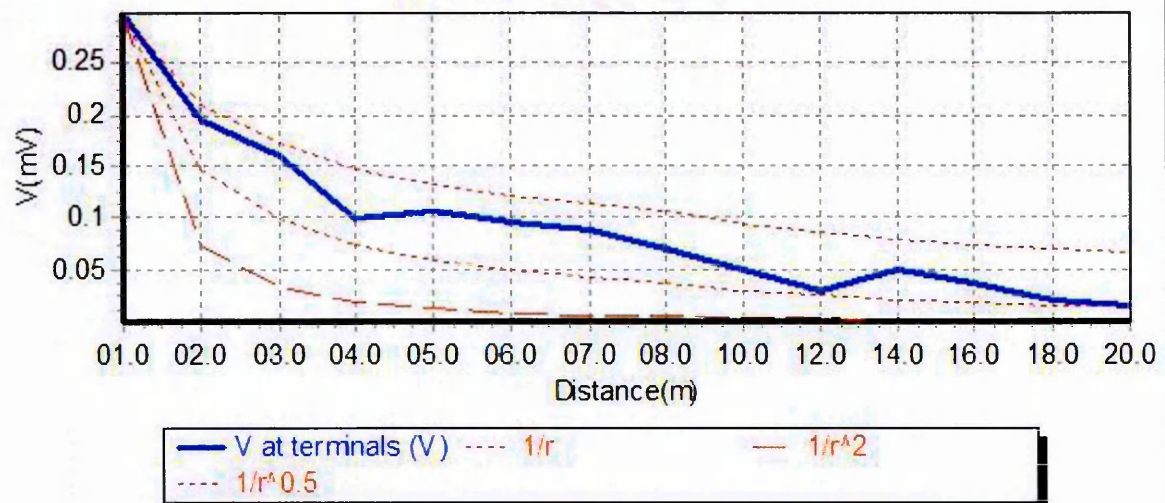
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 7,052,800 Mhz



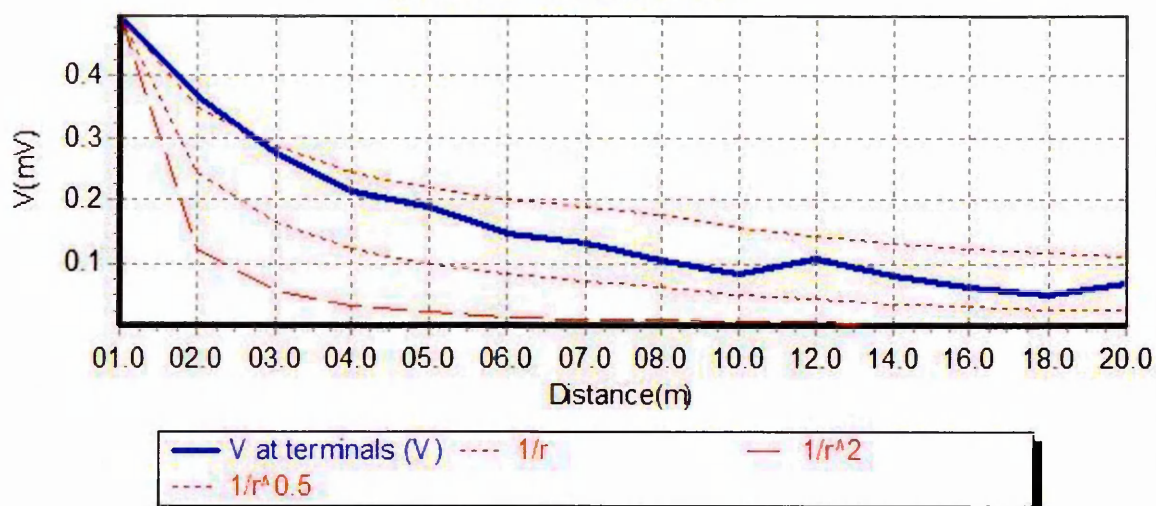
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 8,075,200 Mhz



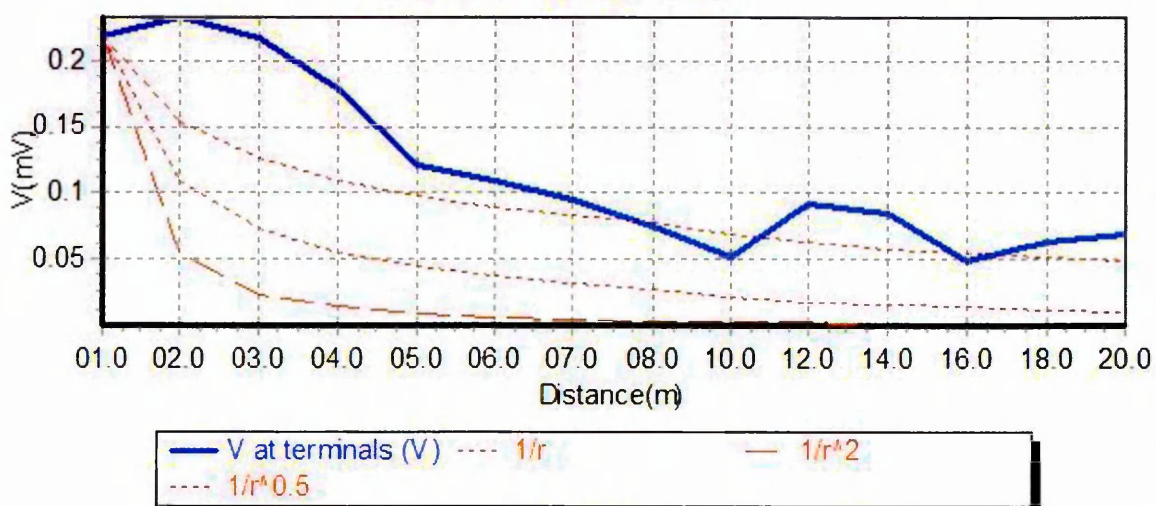
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 9,097,600 Mhz



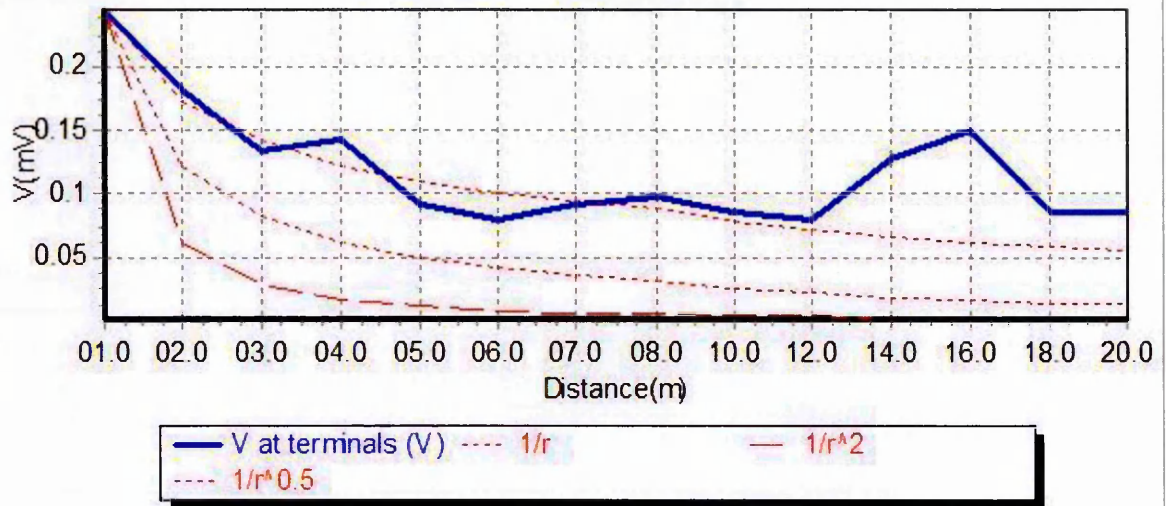
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 10,006,400 Mhz



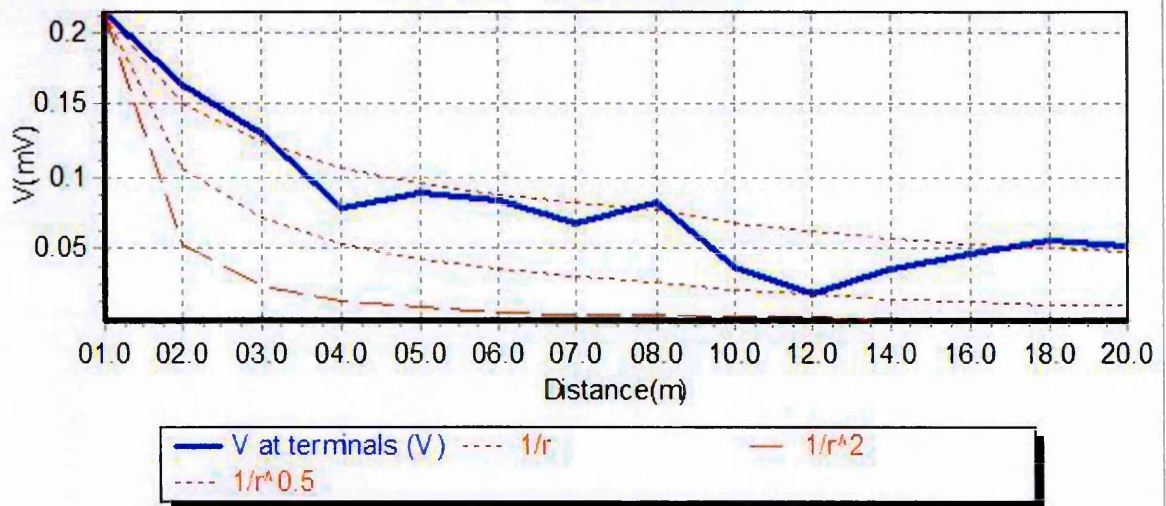
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 11,028,800 Mhz



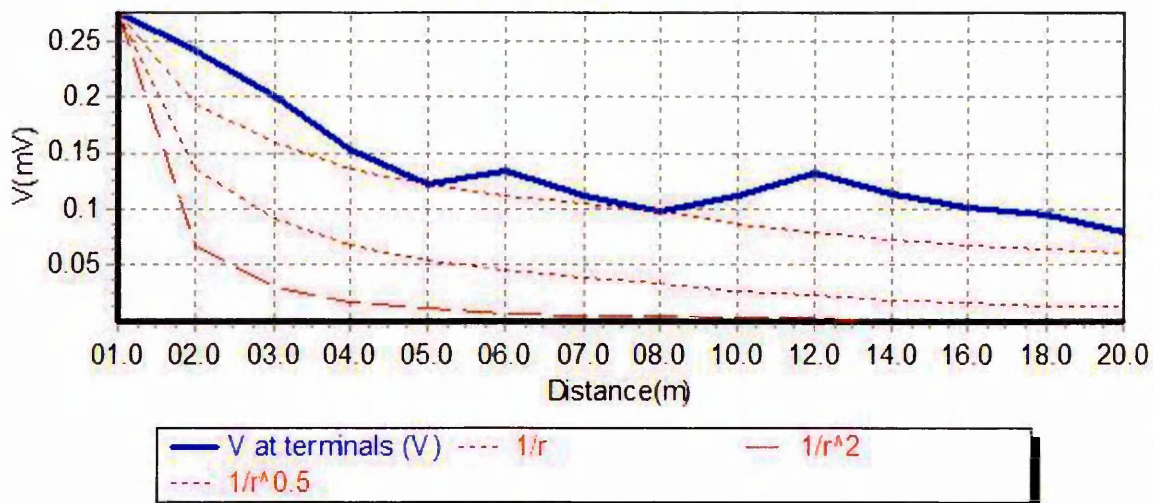
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 12,051,200 Mhz



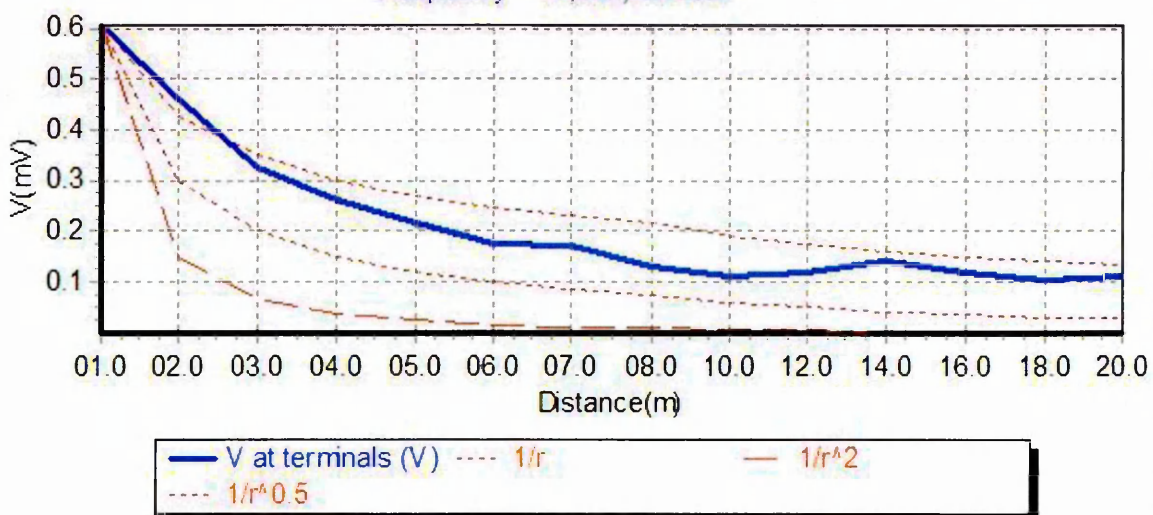
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 13,073,600 Mhz



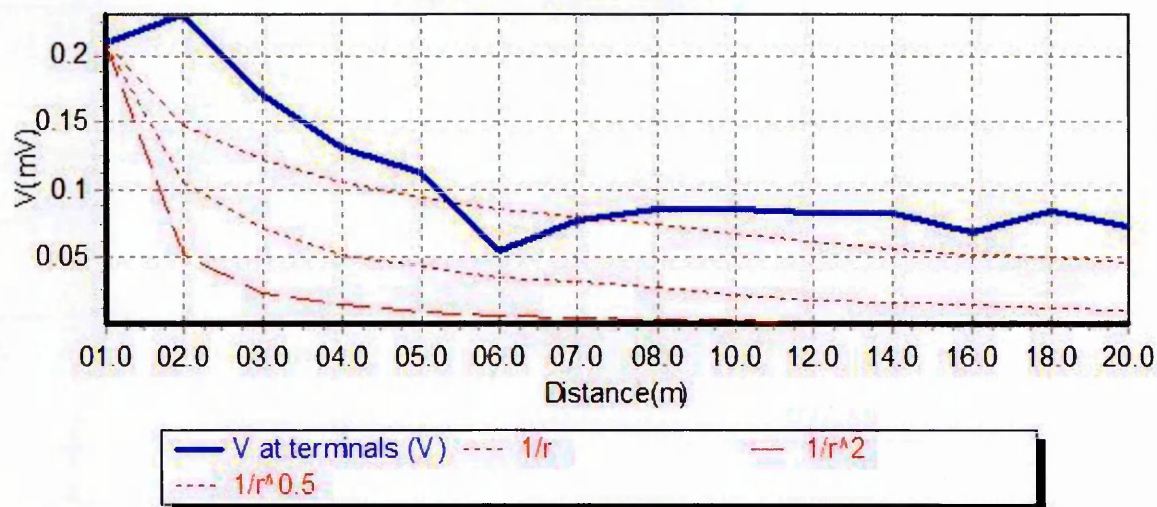
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 14,096,000 Mhz



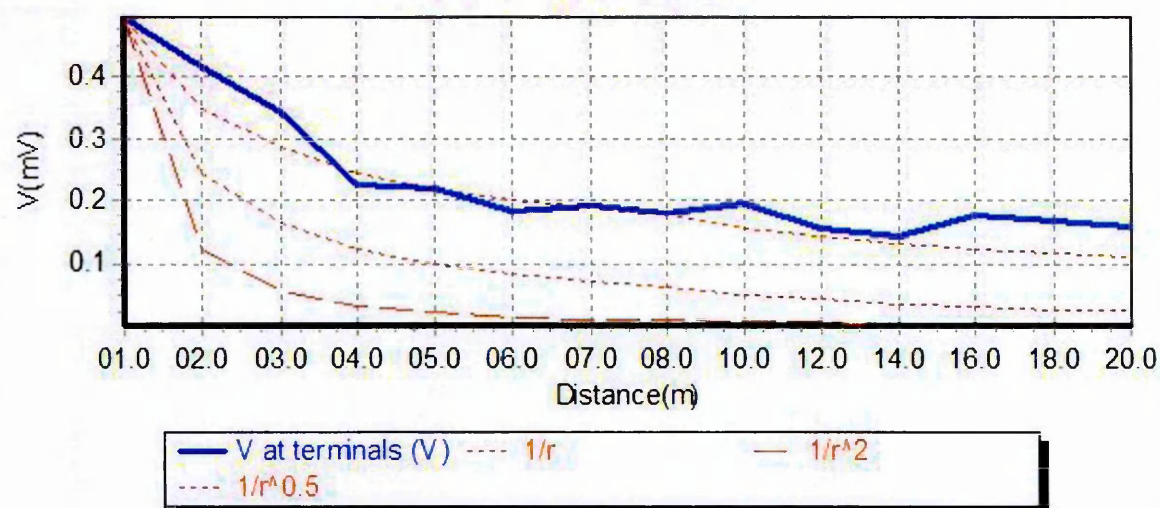
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 15,004,800 Mhz



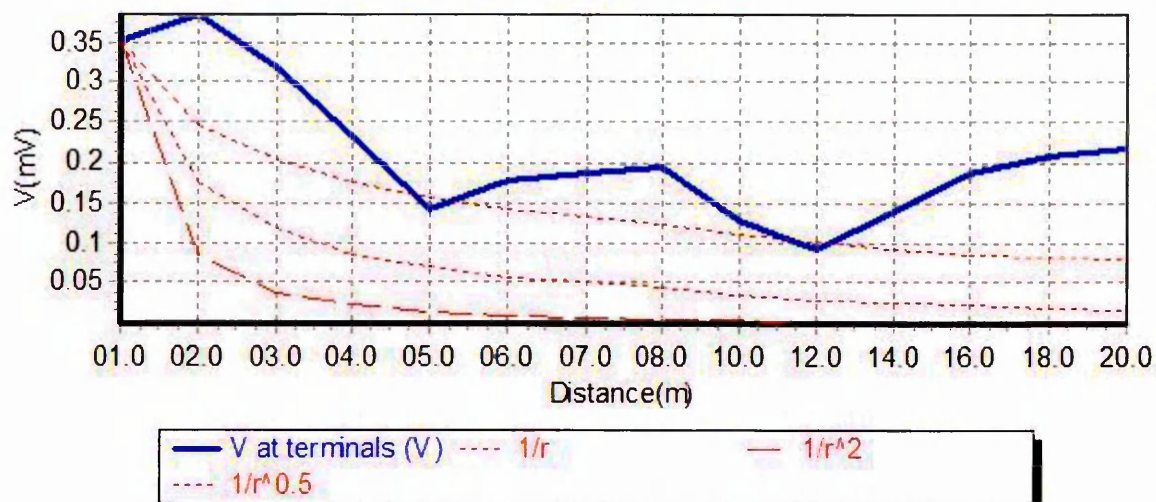
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 16,027,200 Mhz



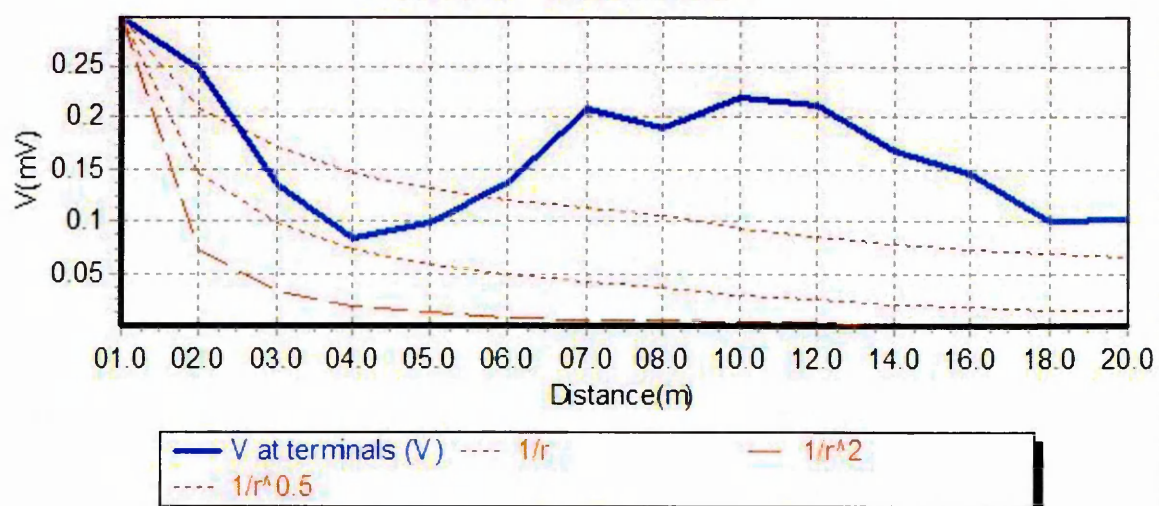
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 17,049,600 Mhz



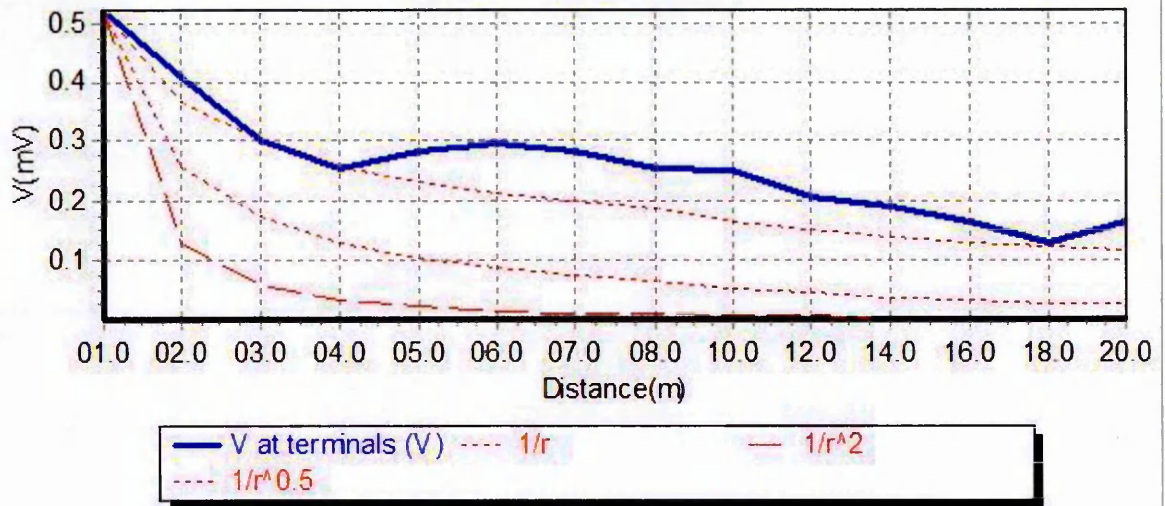
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 18,072,000 Mhz



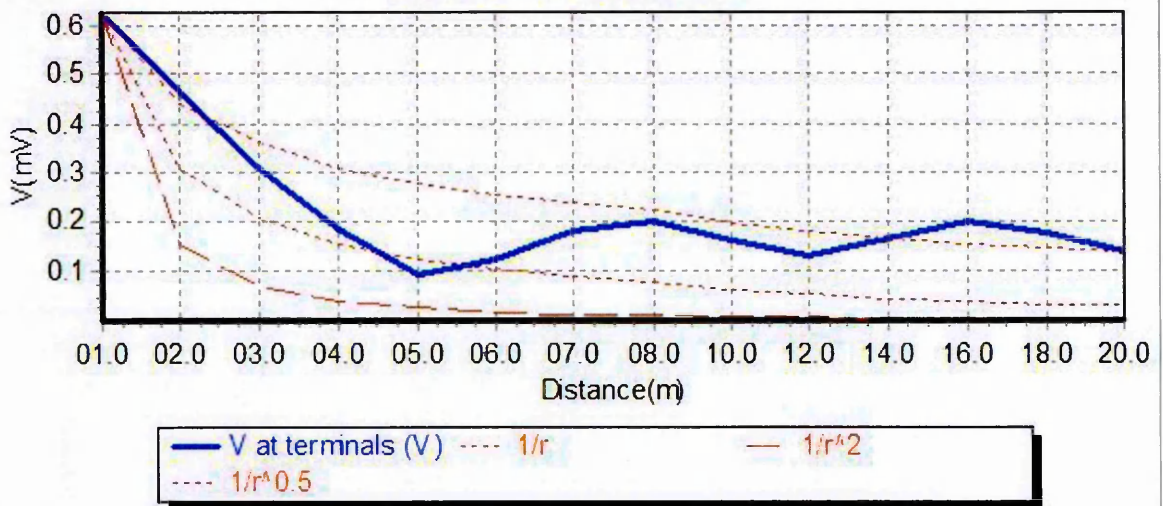
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 19,094,400 Mhz



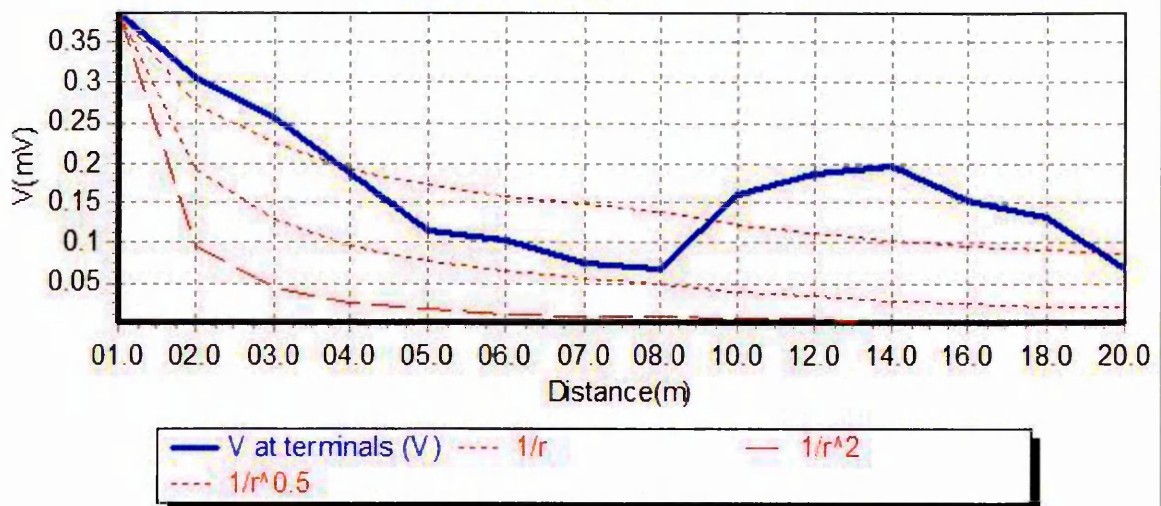
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 20,003,200 Mhz



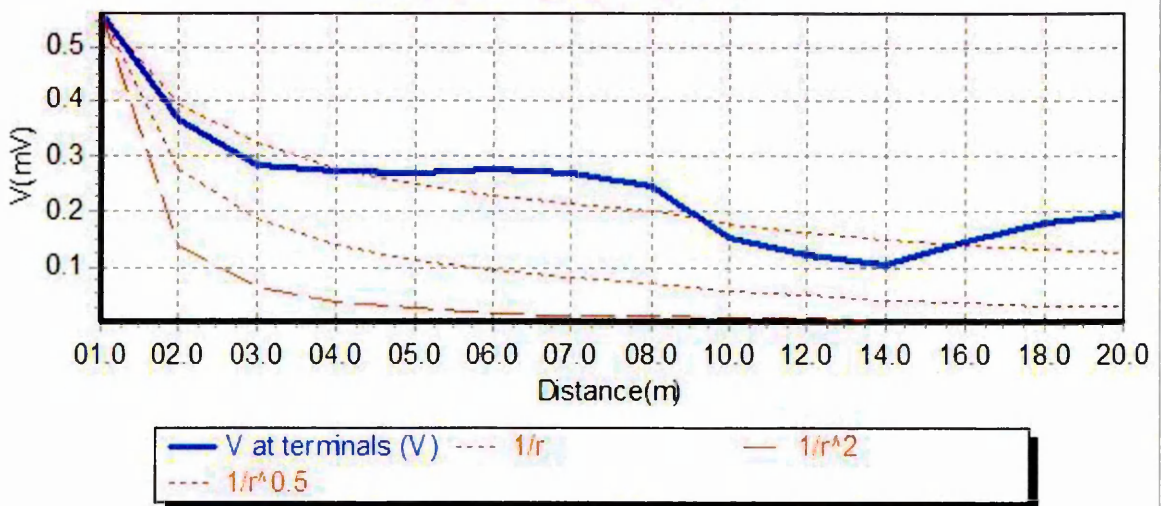
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 21,025,600 Mhz



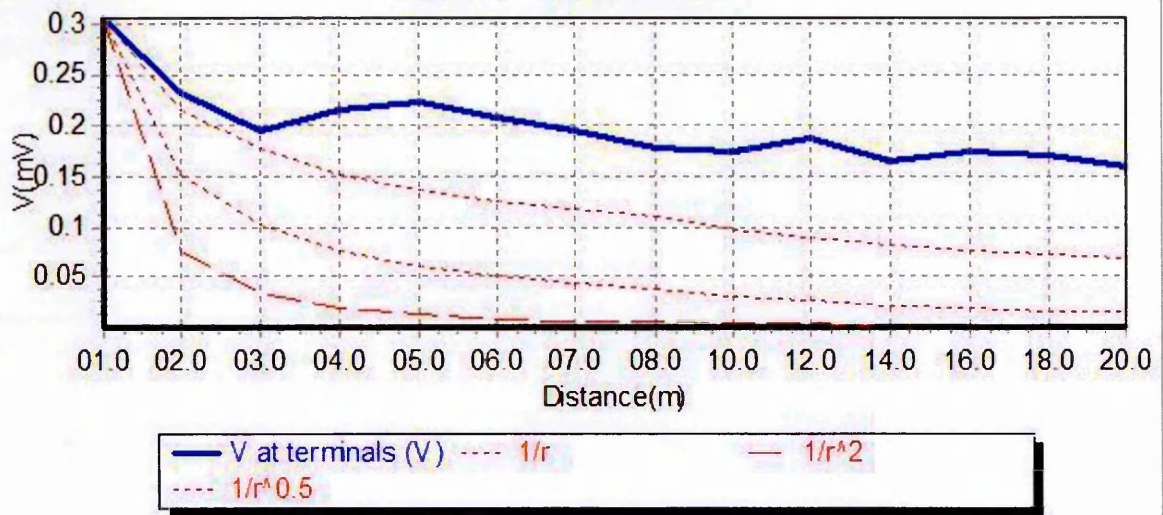
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 22,048,000 Mhz



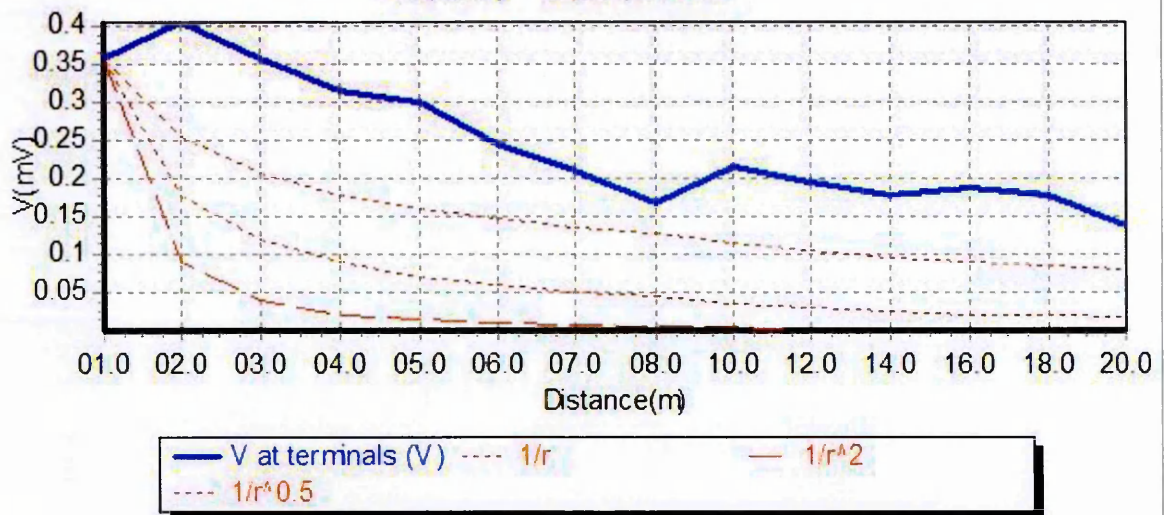
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 23,070,400 Mhz



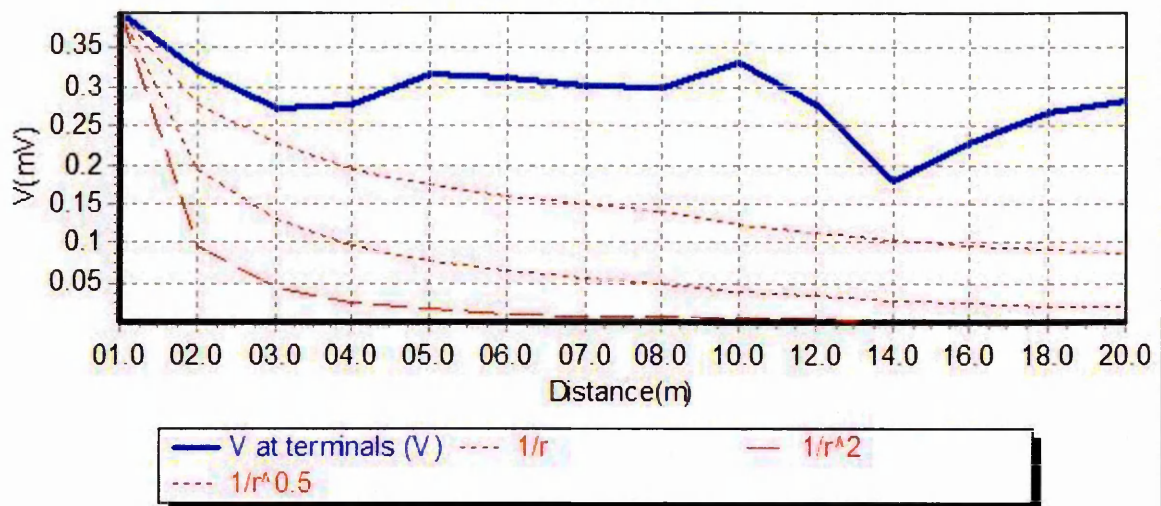
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 24,092,800 Mhz



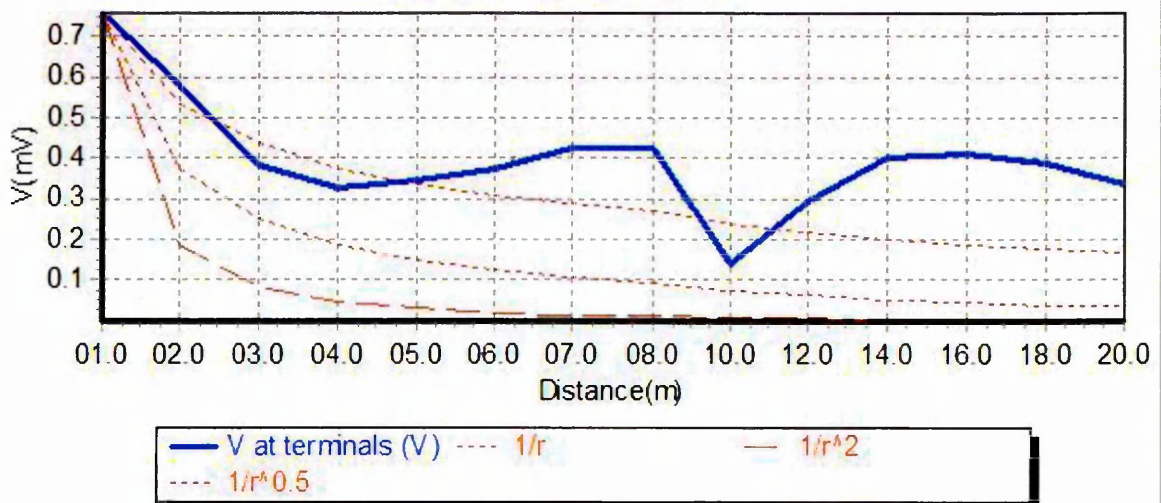
Demonstration of PLT signal attenuation with distance
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 Frequency = 25,001,600 Mhz



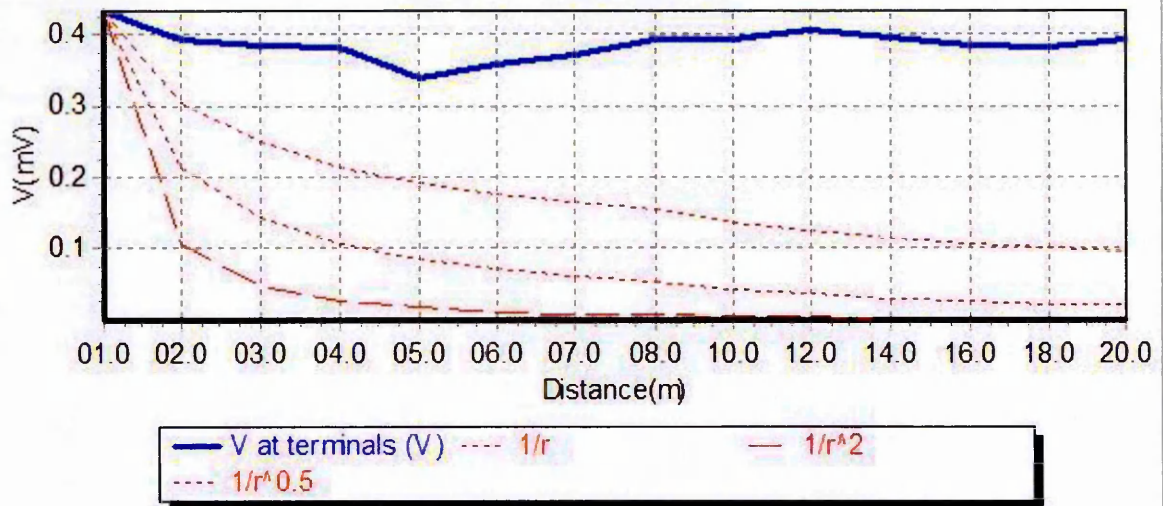
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 26,024,000 Mhz



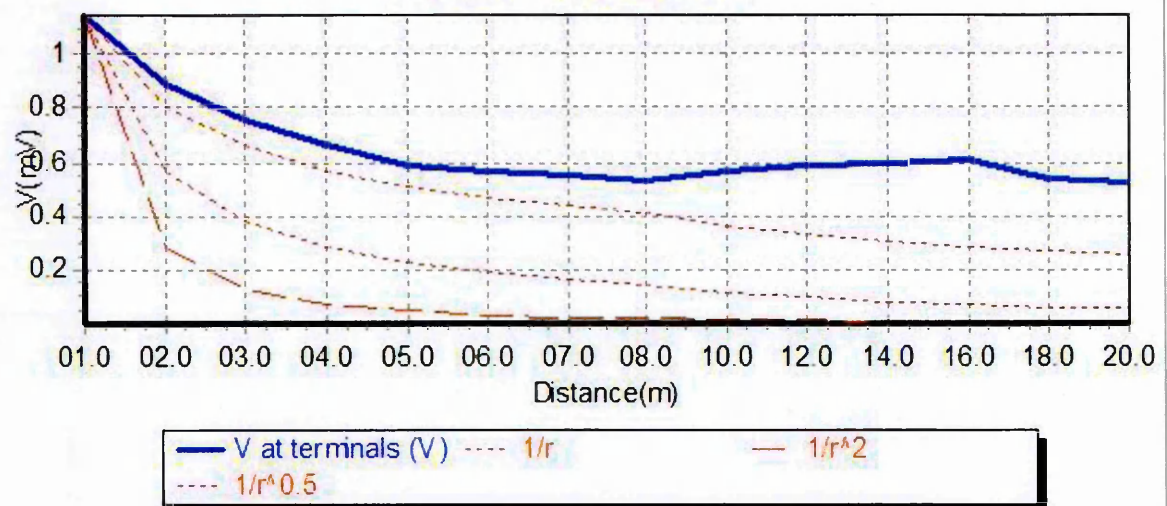
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 27,046,400 Mhz



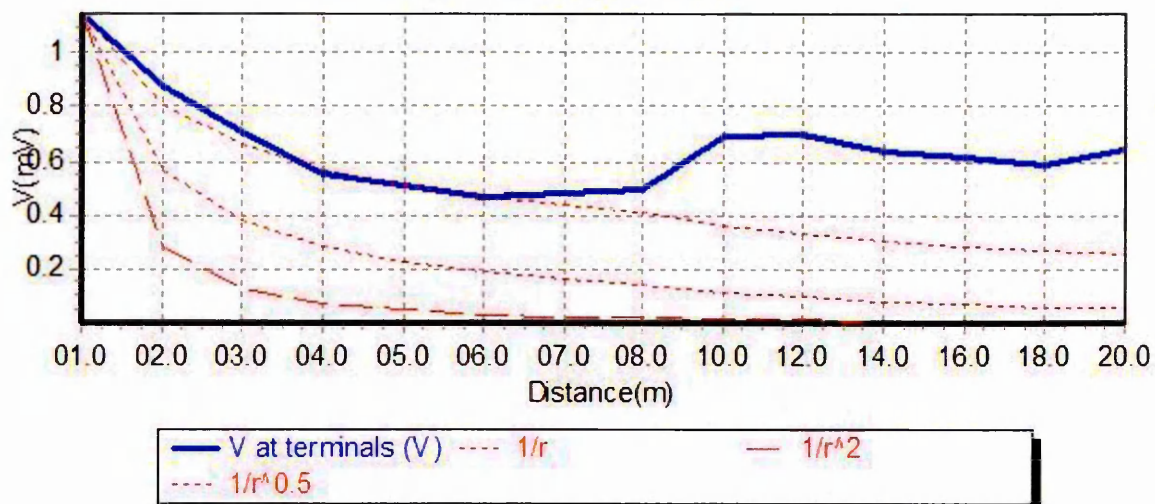
Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 28,068,800 Mhz



Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 29,091,200 Mhz



Demonstration of PLT signal attenuation with distance
 Location = Milton Keynes Antenna Orientation = Vector-sum Date = 02-May-06
 Frequency = 30,000,000 Mhz



APPENDIX I: OTHER FACTORS

The following quotes offer anecdotal evidence that non-engineering factors will influence the regulation of PLT.

UK GOVERNMENT

KEYNOTE SPEECH BY RT HON JEREMY HUNT TO THE UK BROADBAND INDUSTRY (LONDON) – 15 JUL 2010

Thank you all for coming. It has been a confusing couple of weeks for the industry. First the CEO of Google, Eric Schmidt, was in town, telling us that it is now vital that businesses and government build their strategies around the internet. That we “put internet first”. Then we had the rock star, Prince, who informed us that: “the internet is completely over”. As Secretary of State responsible for broadband as well as the music industry I feel somewhat conflicted. But on this one Eric is right and Prince is wrong.

A clear commitment

I hope you are in no doubt whatsoever about how important the Government considers broadband as a part of our economic infrastructure. In his very first speech as Chancellor, George Osborne spoke about the urgent need to address Britain’s creaking broadband network. In his very first speech as Prime Minister, David Cameron spoke about laying the cables of superfast broadband within the next five years as a central Government commitment. And in my own first speech to the sector, I set out how – despite the economic crisis and huge deficit - we will be pressing on to support investment in the superfast network and to bring the benefits

of broadband to everyone in the country. All of us realise that our broadband network is as fundamental to Britain's success in the digital era as the railway network was in the industrial age. All of us share the ambition that, by the end of this Parliament, this country should have the best superfast broadband in Europe and be up there with the very best in the world. We are dead serious about making this happen. Let me tell you why.

The best foundations for growth

In the run up to the general election I had the chance to do a lot of travelling around the country and to speak to a lot of people. Everywhere I went, worries about the economy were the first thing on people's minds. People wondering where the new jobs will come from; Where the new businesses will come from; Or where the new growth sectors of the economy will lie. Shakespeare said "Fear not for the future, weep not for the past." If we are to embrace a radically different economic future, we must recognise that a substantial part of the answer to these questions lies with the digital industries: Industries that already generate 10% of the UK's Gross Value Added – around £130 billion. Industries that already employ 6% of the UK's workforce – more than 1.7 million people. Industries that have kept growing through the downturn, and that will continue to grow rapidly in the years ahead – by an estimated 4% each year.

But in this economic climate, we simply cannot afford to shackle the development of our highest-potential industries by failing to put the fundamental architecture for growth in place. That means introducing measures right away to ensure the rapid roll-out of superfast broadband around the country.

Economic impact

What exactly will this mean for jobseekers, for small-business owners, and for our local and national economy? The Information, Technology and Information Foundation has calculated that a government investment of £5 billion in next generation access would create nearly 300,000 jobs. NESTA says that universal superfast broadband would create double that number, and add £18 billion to the UK's GDP. Some estimates say that in California – an economy roughly the size of the UK – next generation access will generate 2 million new jobs. We only have to look back at the impact of first generation broadband to see that these are not fanciful figures. First generation access provided a boost to our economy of some 0.5% to 1% per year, and meant that, over a four year period, employment grew 1% more in communities with broadband than in those without. It also boosted British productivity. Firms that took up broadband early were 22% more productive than those that didn't. Of course we cannot fully predict the economic benefits and innovation that next-generation broadband will bring. But to quote the great British author, Theodore Hook: "The best way to predict the future is to invent it". And I am determined that we start bringing the benefits of superfast broadband to bear on the British economy right away.

Social impact

But, with this commitment, the Government has far more than just economic benefits in our sights. We are determined to deliver social benefits as well. Today, there are around 40 million internet users in this country, including 30 million who use it every day. People with broadband at home now value it more highly than their land line, mobile phone or digital TV. Most say that they couldn't do without it. Yet there are still 10 million people in this country who have never used the internet.

That's one adult in every five. And, of these, four million are not only digitally excluded, but socially or economically excluded too. These are the people hardest hit by Britain's digital divide. The people who, every day, are missing out on the massive advantages that the rest of us take for granted: Like the consumer savings of more than £550 that we make each year, thanks to online offers and the cheapest deals on everything from energy to home insurance; Like the rapid, timely public information we receive on issues such as transport services and the swine flu outbreak; Like the seven million jobs that were advertised online last year and the earnings uplift of up to 10 per cent for those who are web-literate – meaning an average lifetime earnings increase of £12,000. That's why David Cameron has appointed Martha Lane Fox to be the new 'UK Digital Champion' – with the task of closing the digital divide and getting the whole of the country online.

But Martha also has an additional role, working with Francis Maude as part of the Government's Efficiency and Reform programme. And that is to challenge government departments and the wider public sector to "think internet first" and make much faster progress in getting services online

Getting government services online

Right now, the government is battling to bring down the greatest peacetime budget deficit this country has ever faced. In this incredibly tough environment, we can simply no longer afford to ignore the massive cost savings of communicating and interacting with people online. On average, each of us has three or four interactions with the Government each month. By getting just one of these done online – rather than by phone, on paper, or face-to-face – we can make savings of at least £1 billion every year. Tax returns are the perfect example. They are now almost 100 per cent digital and a great model for how key services can be delivered more cheaply and efficiently. Parents can now also apply for their children's school places online –

something that Martha has challenged all local authorities to make an online-only service in the next few years. That's why Martha and I will be working closely with Francis over the next few months to support the faster migration of Government services online as a way of signalling our commitment to this agenda, and to help drive take up of new broadband services. We will report on our progress early next year.

The government's role

So broadband and next generation access are absolutely vital to the government's agenda..Let me now be clear about the role the government will play. As George Osborne said in the emergency budget: "A genuine and long-lasting economic recovery must have its foundations in the private sector". When it comes to superfast broadband, there is no question that the market must lead the way. That's why I strongly welcome Virgin Media's announcement that they will start to roll out a 100Mbps service by the end of the year – available to about half of homes in the UK. And why I also strongly welcome BT's announcement of an extra £1 billion investment in infrastructure upgrades – extending its optical fibre roll out to reach two-thirds of the UK by 2015. But we have always recognised that government must do its part as well: To ensure that superfast broadband is available to the third of the population that the market may otherwise struggle to reach; To drive private sector investment by making the regulatory changes that will bring down the cost of roll-out; To drive demand by using Government services as a vehicle to speed take up. And we are ready to take radical decisions to make that happen.

Government action

Last month, I announced that we were supporting a universal service level of 2 Meg

as the very minimum that should be available. I have looked at the provision the Government had made to achieve this by 2012. And I'm afraid that I am not convinced that there is sufficient funding in place. So, while we will keep working towards that date, we have set ourselves a more realistic target of achieving universal 2 Mbps access within the lifetime of this Parliament. But I also announced something else: Our plans to establish a series of Rural Market Testing Projects. Our aim is to use these to discover exactly what needs to be done to make superfast broadband commercially viable in rural communities as well as urban areas, and to understand what kind of Government support will be necessary. Right now I am working with my staff to pick out the best locations for these projects – the ones that will allow us to test out different types of solution in different types of rural and remote areas. I have asked for the procurement process to start in the autumn, so that the first projects will be in place by this time next year. I also announced last month that we want to cut the costs of investing in superfast broadband networks by opening up access to the existing infrastructure of telecoms and utilities companies. Today, we published our latest thinking on this – the challenges and opportunities, the risks and rewards. Now we want you to take a look and tell us what you think. What kind of changes could we make to the legislative framework, or what other kind of regulatory support could we provide? How best can we leverage the investment already made in public sector networks to bring down the cost to business? Should we make it a requirement for utilities companies like Thames Water, for example, to lay empty fibre pipes every time they dig up the roads to avoid having to go to the same expense again?

Conclusion

To make this process work best for you, we need you to be as bold and as ambitious as possible. Tell us exactly what you believe needs to be done to make

investing in superfast broadband cheaper and more attractive, and to speed up the roll out of next generation access nationwide. We will be happy to listen. And we will be happy to consider the action that you want. Based on your feedback, we will come back in September with a clear plan for the legislative change that we need, and a clear timetable for making it happen.

REFORM SPEECH BY RT HON JEREMY HUNT TO THE UK BROADBAND

INDUSTRY (LONDON) – 06 December 2010

A few weeks ago I was in Silicon Valley meeting with the CEOs of some of the world's most innovative, high-tech companies. I remember talking to a partner in a venture capitalist firm that has successfully backed companies like Apple and Google, Pay Pal and YouTube. He was in his late 40s, but he told me that the difference between Silicon Valley and Boston was that: "There they think only people over 25 are smart. Here we think it's only people under 25". We may have a young Prime Minister but the truth is that London and the UK weren't even on his radar. It made me ask myself: what part does Britain want to play in the digital revolution? Do we want to be the perennial "first follower" to America? Or can we do better? I hope that, after six months, the government's direction of travel on this is clear. Within a month of my appointment I set out our ambition to have the Europe's best superfast broadband by 2015. Then we announced four rural superfast broadband pilots in the Highlands and Cumbria, Herefordshire and North Yorkshire. We settled the television licence fee in record time, increasing public investment in high speed broadband from £200 million to £830 million. And last month the Prime Minister unveiled our plans for a new Tech City in East London and the Olympic Park – with support from companies such as Google and Facebook, Intel and McKinsey. Today I want to put flesh on the bones of our ambitions. But first I want to

explain why we believe that this agenda is so central to our strategy for economic growth.

Economic growth: laying the foundations for risk-taking

Back in October, David Cameron set out his plans to restore our economic dynamism. Anyone who has seen the film *Social Network* will not need reminding that we live in an age when companies with the smallest of investments can become global giants overnight. This world is not foreign territory for the UK. Our digital industries already generate 10% of our Gross Value Added – around £130 billion. They already employ around six per cent of the UK's workforce – more than 1.7 million people. And they have already demonstrated their incredible potential by growing through the downturn – growth that is set to continue in the years ahead by an estimated four per cent each year. We are the acknowledged global leader in e-commerce – spending more online per capita than any other country in the world. Our businesses are successfully exploiting the internet to expand their sales overseas – exporting £2.80 for every £1 imported, compared to 90 pence for every £1 in the offline economy. And our consumers are highly active online. We now have 40 million users of the internet, broadband penetration has doubled in the past five years, and 70 per cent of households are broadband subscribers. But, at the same time, we face significant barriers to growth. The country the world envies for its skills in creating digital content lags alarmingly behind when it comes to monetising it. Our broadband infrastructure is towards the middle rather than at the head of the pack. Only 15 per cent of UK subscribers currently have speeds above five mbps, compared with 65 per cent in South Korea. And only 0.2 per cent of UK households had a superfast broadband connection at the end of last year – compared to 12 per cent in Sweden and 34 per cent in Japan. And when it comes to Bill Clinton's "Digital Divide" we are the country with 30 million people who go online every day and nine million people who haven't been online

once – that’s more than the population of our five largest cities. These are all big challenges. Today I want to focus on an area where I believe the government has a pivotal role to play – namely in ensuring that we have world-class digital infrastructure in place. The LSE believe a superfast network will create 280,000 new jobs, while NESTA believe it will be more like 600,000. The Federation of Small Businesses believes it could add £18 billion to GDP. The potential is huge. But when I spoke to Jonathan Ive, the British Head Designer at Apple based in California, he told me that, unless you take extraordinary risks, you won’t survive in the digital world. I want our broadband infrastructure to make it possible for our entrepreneurs and investors to take those risks. To draw on what Shakespeare once called “The natural bravery of our Isle”, and use it to develop the commercial applications, products, services and content that will dominate in the high-speed world. The best superfast broadband network in Europe? Yes, but not as an end in itself. As the foundation for a new economic dynamism that will be at the heart of our future economic success.

Public services reform

But this is not just about economic growth. I am particularly pleased to be launching our strategy for superfast broadband at Reform today because it is also central to our agenda for public services reform. Already we can see how other countries are using next generation access to transform the delivery of public services. Australia, for example, where higher speed broadband has led to the School of the Air – a distance learning initiative which brings together students from remote areas in online classrooms. Or South Korea, where the Education Broadcast Service means that children who can’t afford to go to “cram schools” to prepare them for the crucial, national aptitude test can still access high quality educational tutorials online. Or America, where Snap! VRS uses teleconferencing to connect deaf citizens with sign language interpreters who can help them during medical consultations or with other

services. "Ons Net" in The Netherlands is another good example. By taking fibre to the home for all residents of the small town of Nuenen, it has allowed a whole host of new services to develop and help raise their quality of life. From telecare systems for the elderly to live streaming of church services; from web applications for Alzheimer's sufferers to virtual fitness coaching and local TV – there are countless examples of how superfast broadband is helping them to build a fairer, as well as a more prosperous, society. And we are already getting glimpses of that future here in the UK. At Alston Healthcare in Cumbria, for example, where medical staff are using next generation broadband to diagnose, treat and monitor remotely, while their patients are using it to book GP appointments and arrange repeat prescriptions via their TVs. Last month we announced that digital will increasingly be the default channel for delivering public services – just as it is for many service in the private sector. And as part of that, we announced a first wave of services that will have digital as their primary delivery channel – including student loans and jobseeker's allowance applications for individuals, as well as VAT registration and Companies House services for businesses. For providers, digital is cheaper and more efficient. With Jobseeker's allowance alone, the Department for Work and Pensions is expecting to save up to £100 million of taxpayers' money by 2014-2015. For users, digital is simpler, more convenient and more personalised. That's why Martha Lane Fox, as the UK's Digital Champion, has the goal of closing the digital divide and making this country the first in which everyone has the opportunity to access the internet. Her campaign – Race Online 2012 – is making a real impact, working with more than 900 partners from all sectors. Just last week, Microsoft launched their "Give someone their first time on the web" initiative – opening up new opportunities to get people online, provide them with training, and even offer them your old PC. Closing that digital divide, and making that shift to online delivery, has the potential to transform the relationship between individuals and government; Putting more power into the hands of citizens, and giving communities the tools they need to build

a bigger and stronger society.

A strategy for Britain's superfast broadband future

So much for the "why?". What about the "how"? Of course, it's not the Government's role to tell businesses what to do. Already, the market in the UK is making great strides in delivering superfast broadband. With Virgin Media and BT rapidly deploying networks, nearly 50 per cent of households can now access speeds of 50Mbps. At the same time, smaller providers such as Rutland Telecom, Vtesse and Geo are finding innovative ways of delivering superfast broadband in areas where the economic climate is more of a challenge. But the Government does have a key role to play in stimulating competition and catalysing investment in the new infrastructure we need. That's why, in the recent spending review, we announced £530 million of funding to support broadband rollout – with the potential for making an extra £300 million available for the period 2015-2017. The strategy we are publishing today represents our plan for how to spend it in a way that will stimulate the greatest possible investment in our superfast broadband network. That means opening up access to existing infrastructure, including BT's network of ducts and poles. It means working with local authorities to reduce the cost of broadband rollout by clarifying existing guidance on streetworks and micro-trenching. It means issuing new guidance for builders and contractors on how to make sure new buildings are broadband ready – and I'm pleased to say that the British Standards Institution and the Building Research Establishment, who have led this work for us, have brought out that guidance today. And, at a time when half of all new web connections are mobile connections, it means awarding the 800MHz and 2.6GHz spectrum to allow the development of the next generation of mobile service.

A fibre point in every community

Technology neutrality is a central part of this strategy. No single technology will be suitable for all circumstances, and a mix of technologies – fixed, wireless and satellite – will be needed if we are to deliver on our ambition throughout the UK. But at the same time we recognise that taking high-capacity fibre deeper into the network is likely to be key – which is why our goal today is very simple: to deliver a fibre point in every community in the UK by the end of this parliament. In order to help achieve this, I can announce that we will be making up to £50 million of funding available for a second wave of superfast broadband market testing projects – to add to those that we have already established in North Yorkshire and Herefordshire, Cumbria and the Highlands and Islands. We will be inviting local bodies and devolved administrations right across the UK to propose new testing projects in April of next year, with a view to making a final selection in May. I am giving everyone advanced notice of this to allow local communities time to develop broadband strategies and work out which projects they need the most. I am also very pleased to be able to say that we have been having constructive discussions with BT and the BBC about the role they can play in fulfilling these ambitions. The BBC recognise that, as one of the biggest drivers of demand for broadband through the iPlayer, the licence fee has a big role to play. But they are doing much more and have indicated they are considering funding outreach and education programmes in the areas where we have pilots. As a result, they have announced a series of new initiatives. A one Gigabit per second trial in Kesgrave, near Ipswich, early in the New Year – a speed that can download a two hour film in just 12 seconds. An extension of their highly successful “Race to Infinity” campaign.

A decision to include up to 40 market towns in rural areas in their next phase of superfast broadband deployment in late 2011 and early 2012. And last, but by no means least, a signal that they intend to bid for our £830 million investment by matching it with a similar investment. According to their analysis, this matched fund

will ensure that superfast broadband will reach 85-90 per cent of the country. It's a great example of how public investment and government action can stimulate further investment from the private sector. And it's an achievement that will take us well on the way to creating Europe's best superfast broadband network.

Conclusion

Let me finish by saying a few words about what we mean by the word "best". The broadband scorecard developed by the Berkman Centre at Harvard focuses on three areas – speed, coverage, and price. To that, we are adding an additional factor: choice. If, by the end of this parliament, we are performing across these four areas then we will have met our ambition. But in reality "best" means more than just a measurement against a set of indicators. It means more than a broadband network that will help us to secure and underpin our economic future. One that can put the UK right up there with the rest of the world when it comes to internet innovation. It means one that will make sure that everyone can benefit from being online, and that no one is excluded. Like the young man from Leeds who told Martha Lane Fox that the opportunity to learn how to make and sell music online had turned his life around after drug addiction. Without the internet, he said, he "would be dead". Or the woman in her 80s I met in Downing Street in the summer who told me that getting online had, quite simply, stopped her from feeling lonely. New technology is not perfect. It is a force that needs to be carefully harnessed. But in the end we should remember that its benefits are not just about efficiency, or growth, or jobs but about a lasting, positive impact on each of our daily lives. A positive impact that the Government is determined to make possible.

UK INDUSTRY

Virgin Media Press Release – 27 Jul 2010

Virgin Media today announced that residents of the Welsh village of Crumlin, Caerphilly, will be the first in the UK to trial ultrafast broadband delivered over existing electricity poles. Following a landmark agreement with Surf Telecoms, a Western Power Distribution company, homes in the village of Crumlin will be connected directly to Virgin Media's fibre optic network, effectively increasing local broadband speeds ten-fold* in a community that has previously relied on BT's copper infrastructure. As well as 50Mb broadband, villagers will be offered Virgin Media's TV service, including around 5,000 hours of catch up TV and on demand content. The trial will start next month and is scheduled to run into 2011.

The agreement with Surf Telecoms marks the first use of existing commercial infrastructure to aurally deliver ultrafast broadband to a community currently beyond the reach of a fibre optic network. Virgin Media began trialling aerial deployment in the Berkshire village of Woolhampton in March this year using purpose-built infrastructure. The trials are part of Virgin Media's efforts to expand its network and identify ways of bringing next generation digital services to people who live in rural or harder to reach areas of the UK. Initial analysis suggests that 'non-traditional' approaches of the kind being explored in Crumlin and Woolhampton could, with some focused measures from government, significantly accelerate delivery of next generation broadband to millions of extra homes right across the UK.

Jon James, executive director of broadband, Virgin Media, said: "We're already bringing broadband speeds of up to 50Mb and, soon 100Mb, to over half of all UK homes and are pushing the boundaries to ensure that homes right across the UK benefit from ultrafast broadband. Working in partnership with companies like Surf Telecoms, we can more rapidly and efficiently expand the reach of fibre optic networks to towns, villages and communities right across the UK."

Richard Doble, Design and Policy Manager, Surf Telecoms, said: "Western Power Distribution's electricity infrastructure reaches over 2.5 million homes across South West England and South and West Wales and, with this trial, we're exploring an innovative new approach that could bring ultrafast broadband to many customers for the first time. The possibilities of aerial deployment promise a valuable use of existing infrastructure and an interesting new commercial opportunity for utility companies. We're pleased to be at the forefront of this innovation."

Virgin Media has previously announced plans to extend its cable infrastructure, which today passes more than half of all UK households with speeds of 10Mb, 20Mb, 50Mb and, soon 100Mb, to 500,000 new build homes.

Virgin Media believes small changes to the regulatory environment, such as the streamlining of duplicated planning processes, a more transparent way of calculating wayleave payments, access to BT poles and ducts, and clarification of the Electronic Communications Code, aerial deployment could significantly improve the viability of delivering next generation digital services to rural communities across the UK.

On 15 July 2010, the Government published a discussion paper looking at barriers to the deployment of superfast broadband in rural areas of the UK. Over the past two years, Virgin Media has run a number of trials aiming to provide valuable insight into the technical, operational and commercial viability of delivering superfast speeds in rural areas. In 2009, Virgin Media launched a trial in Cornwall which brought next generation services to the villages of Hatt and Saltash by running fibre optic cable underground to BT's local street cabinets. In March 2010, Virgin Media launched a trial in Woolhampton, Berkshire to test the technical feasibility of aerially delivering next generation broadband services across telegraph poles.

About Virgin Media

With almost 10 million customers, Virgin Media is the UK's first quad-play provider of broadband, TV, phone and mobile. The company is one of the largest residential broadband providers in the UK, using a unique fibre optic cable network to deliver next generation ultrafast internet access of up to 50Mb to just over half of all homes. Combined with a high speed ADSL service and mobile broadband products, Virgin Media is able to offer broadband internet access to virtually the entire country. Virgin Media has the UK's most advanced TV on demand service and was the first TV platform to carry BBC iPlayer. It is the second largest provider of pay TV, was the first to launch a high definition TV service and offers a high-specification, HD-ready V+ personal video recorder. The company operates the most popular virtual mobile network in the UK which, when launched, was the world's first such mobile phone service. It is also one of the largest fixed-line home phone providers in the country. Virgin Media Inc. is listed on the NASDAQ Stock Market and the London Stock Exchange (VMED).

About Surf Telecoms

Western Power Distribution group company, Surf telecoms is an established, utility backed telecommunications infrastructure provider. Much of the Surf telecoms' fibre optic network is installed upon the electricity distribution infrastructure of Western Power Distribution, which serves 2.6 million customers across South Wales and the South West of England. Surf telecoms provides quality, high capacity core telecommunications infrastructure and services to communications service providers, broadband ISP's , broadcasters, communications intensive businesses, utilities, corporate sector business and key public sector services including education and health.

SOURCE: Virgin Media

USA

PRESS RELEASE BY THE WHITEHOUSE – 18 AUGUST 2010

Vice President Biden today announced 94 Recovery Act investments in broadband projects that will create jobs and expand economic opportunities within 37 states.

These investments in high-speed Internet infrastructure will help bridge the technological divide in communities that are being left in the 20th century economy and support improvements in education, healthcare, and public safety. Today's announcement, an investment totaling \$1.8 billion, is part of a nearly \$7 billion Recovery Act initiative.

"Today's investment in broadband technology will create jobs across the country and expand opportunities for millions of Americans and American companies. In addition to bringing 21st century infrastructure to underserved communities and rural areas, these investments will begin to harness the power of broadband to improve education, health care, and public safety," said Vice President Biden. "The awards are another great example of how the Recovery Act is creating jobs upfront, while also building a foundation for sustainable job creation and global competitiveness."

The projects receiving funds today are part of a program – administered by the Department of Commerce's National Telecommunications and Information Administration (NTIA) and the Department of Agriculture's Rural Utilities Service (RUS) – to expand broadband access and adoption across the country. "The broadband investments announced today are going to put people to work in the near term, but they also will lay the groundwork for sustainable economic growth down the road," U.S. Commerce Secretary Gary Locke said. "These projects will connect Americans who have for too long been without the full economic, educational and social benefits of high-speed Internet access – access central to success in the 21st Century." "The broadband projects announced today will give rural Americans access to the tools they need to attract new businesses, jobs, health care and

educational opportunities,” Secretary of Agriculture Vilsack said. “The Obama Administration understands that bringing broadband to rural America provides a gateway for businesses and key anchor institutions – such as libraries, schools, public safety and community centers – to provide services to thousands of Americans. These projects will create jobs building these networks, and the completed systems will provide a platform for rural economic growth for years to come.”

Today’s announcement includes 66 grants awarded by the Commerce Department for projects to deploy broadband infrastructure and connect community anchor institutions to broadband, create and upgrade public computer centers, and encourage the sustainable adoption of broadband service. It also includes 28 awards from USDA for broadband infrastructure and satellite projects that will provide rural residents in 16 states and Native American tribal areas access to improved service. The Department of Commerce awards also contain grants for public safety broadband networks that will improve response times and communication at the scene of emergencies. These projects constitute a critical set of demonstration projects and a head start on President Obama’s commitment to support the development of a nationwide, interoperable public safety wireless broadband network. According to an analysis released by the National Economic Council last year, overall Recovery Act investments in broadband are expected to create tens of thousands of jobs in the near term and expand economic development and job opportunities in communities that are being left behind in the new knowledge-based economy. Recovery Act broadband projects help bring down the cost of private investment, attract Internet service providers to new areas, improve digital literacy among students and workers, and help create new opportunities in employment, education, and entrepreneurship by wiring homes and businesses. With new or increased broadband access, communities can compete

on a level playing field to attract new businesses, schools can create distance learning opportunities, medical professionals can provide cost-efficient remote diagnoses and care, and business owners can expand the market for their products beyond their neighborhoods to better compete in the global economy.

President Obama signed The American Recovery and Reinvestment Act of 2009 into law on February 17, 2009. It is designed to jumpstart the nation's economy, create or save millions of jobs, and put a down payment on addressing long-neglected challenges so that the country can thrive in the 21st century. The Act includes measures to modernize our nation's infrastructure, enhance energy independence, expand educational opportunities, preserve and improve affordable health care, provide tax relief, and protect those in greatest need.

PRESS RELEASE TO POTENTIAL CUSTOMERS OF MIDWEST ENERGY

SERVING MICHIGAN, INDIANA AND OHIO – DECEMBER 2010

When we last updated you on the status of our Broadband Over Powerline Internet service, we were eagerly awaiting news on our second application for stimulus dollars through the American Recovery & Reinvestment Act to bring a fiber-based project to our service territory. Unfortunately our hopes for funding were dashed yet again. Regardless of what happened with the funding, we knew we would continue to work in some fashion with IBEC, our BPL partner, and are doing just that with a stronger-than-ever resolve to bring an affordable and reliable high-speed Internet option to our service territory. We continue to proceed with caution; again, our desire is to provide a tested and reliable service and until we are satisfied with our ability to do that, we will not open the floodgates. That said, there have been some positive strides made related to service delivery: Over the summer and fall, IBEC began certifying lines on the two substations currently under deployment. Four of seven circuits have passed open certification, meaning we can confidently add customers without concern about speed or reliability issues. We are now offering BPL Ultra to

customers on lines that have been certified. BPL Ultra is 10-20 times faster than dial-up with speeds up to 1 mbps.

As we have shared in previous updates, underground electric facilities have been a major obstacle in our deployment progress. IBEC technicians have worked diligently for many, many months and now believe they can design the system to serve underground facilities without problem. It is a solution still in the testing phase, but will certainly allow us to confidently expand the service. Plans are underway for deployment of a third substation in early 2011. We are not yet releasing details, but will eagerly share once we have the backbone in place so that we can start adding customers immediately. Progress is being made, slowly but surely. I know it's not fast enough when you're sitting in an unserved or underserved area, as so many of our electric customers are. Please believe me when I say we share in that frustration, and will continue to work on your behalf to pave the way for high-speed solutions for customers in our service area.

Sincerely,

Robert L. Hance

President/CEO

Midwest Energy Cooperative

GLOSSARY

ADSL	Asymmetric Digital Subscriber Line
AMN	Artificial Mains Network
ARRL	American Radio Relay League
BBC	British Broadcasting Corporation
BPL	Broadband over Powerline
CENELEC	European Committee for Electrotechnical Standardisation
CEPT	Conference of European Post and Telecommunication Administrations
CISPR	International Special Committee on Radio Interference
COMINT	Communications Intelligence
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access/Collision Detection
DSSS	Direct Sequence Spread Spectrum
ECC	Electrical Communication Committee
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Force
ETSI	European Telecommunication Institute
EU	European Union
EUT	Equipment Under Test
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
GMSK	Gaussian Minimum Shift Keying
GPIB	General Purpose Interface Bus
HF	High Frequency
IEC	International Electrotechnical Committee

ITE	Information Technology Equipment
ITU	International Telecommunication Union
LISN	Line Impedance Stabilisation Network
LLA	Large Loop Antenna
LV	Low Voltage
NAMAS	National Measurement Accreditation Service
NEC2	Numerical Electromagnetic Code 2
NSA	Normalised Site Attenuation
OATS	Open Area Test Site
OFCOM	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
PDF	Probability Density Function
PLC	Powerline Communications
PLT	Powerline Telecommunications
PSCRG	Power Systems Communications Research Group
PSD	Power Spectral Density
RA	Radio-communications Agency
SSE	Scottish and Southern Energy PLC
SHF	Super High Frequency
TDF	Technical Documentation File
TDM	Time Division Multiplexing
UHF	Ultra High Frequency
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
VDSL	Very high bit rate Digital Subscriber Line
VHF	Very High Frequency
WMF	Windows Metafile

xDSL	Any Digital Subscriber Line (such as ADSL/VDSL)
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